DOE/NASA/0012-78/1 VOL. 2
EPRI RP1082-1
NASA CR-159411
GE78TMP-60, VOL. 2

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VOLUME TWO: APPENDICES—SCREENING OF CONCEPTS

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APPENDIX A

BIBLIOGRAPHY AND CROSS REFERENCES

SOURCES

An extensive bibliography of source material has been related to the thermal energy storage concepts and to the utility systems into which they are to be applied. Sources include the Energy Research and Development Administration (ERDA)/Department of Energy (DOE) contractors, National Aeronautics and Space Administration-Lewis Research Center (NASA-LeRC), and Electric Power Research Institute (EPRI) contractors, and computer searches of the literature. The reports were logged as they were received, and assigned a file number chronologically, which has been used during the course of the project. There are various possible ways to access this list. The basic listing given on the following pages is alphabetically by lead author (or by issuing organization when no author is given). The original log numbers have been retained and are used in the text.

For ready cross-referencing, three forms of listing are given in this sequence:

- Numerical Listing
- Alphabetical Listing
- Subject Area

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GE-AEP, 1977	134
Honeywell, 1976	176
Honeywell, 1977	51

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Chubb, Nemecek, and Simmons, 1977	22
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APPENDIX B

TAXONOMY — PROPONENTS AND SOURCES

FOR

CONCEPTUAL DESIGN OF THERMAL ENERGY STORAGE
FOR
NEAR-TERM ELECTRIC UTILITY APPLICATIONS

Rev. 2-1-78

SOURCES OF HEAT

		Proponents	References
1.	**High Temperature Water**		
11.	Feedwater Heating Loop (any point)	1,3-6,8,21,25	108,121,156,128
12.	Boiler Inlet		
13.	Steam Drum in Boiler		
2.	**Steam**		
21.	Extraction Steam (existing FWH points)	25,1	6
22.	Extraction Steam (special or enlarged points)		
23.	Crossover (between IP and LP turbines)		
24.	Cold Reheat (output of HP turbines)		
25.	Hot Reheat (output of reheat, input to IP turbine)		
26.	Live Steam (input to HP turbine)	31,48,22-24	36,71,82,85,105,132,62,61,51
27.	Backpressure Turbine Output		
28.	Turbine Shaft Power and Steam Compressor		Marguerre, Babcock (French)
3.	**Gas**		
31.	Helium (as in HTGR or PBR)	26,49,47	95,149,154,12,13
32.			
33.	Hot Air (as in GT intercool or compressor output)	28	10,11,48, 68,78-80
34.	Stack Gases (as in GT regenerator)		
35.	Fluidized Bed (furnace combustor)		
36.	Heat Pipes (coupling furnace air, helium, or stack gas to TES system)		
37.	Other	42	22,102-104
4.	**Unspecified**	41	19

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STORAGE MEDIA

SENSIBLE HEAT

	References	Proponents
Liquids		
1. High Temperature Water		
11. HTW to 170°C	108,121,128	5,6
12. HTW to 230°C	108,121,156,128	5,8,6
13. HTW to 350°C	26,42	1,2,4
2. Organic Compounds		
21. Oils	38	22
211. Exxon	6,16,17,62,66	21-23,25
212 Dow Chemical		
213. Mobil		
22. Silicones		
221. Dow Corning		
29. Other		
3. Inorganic Compounds		
31. Salts (Molten)		
311. Nitrates		
3111. HITEC	95,108,112	26,29
312. Hydroxides		
319. Other		
32. Sulfur (Molten)	71,82,85,105	31
33. Sulfuric Acid		
34. Metals (Molten)		
39. Other		

	References	Proponents
Solids		
4. Metals		
41. Steel/Iron	91	30
49. Other		
5. Minerals		
51. Silica		
52. Granite		
53. Iron Ore		
531. Feolite		
59. Other		
6. Ceramics		
61. Alumina		
62. Magnesia		
PHASE CHANGE MATERIALS		
7. Organic Compounds		
71. Phthalimide		
79. Other	19	41
8. Inorganic Compounds		
81. Nitrates	132,36	48
82. Carbonates	29	44
83. Fluorides	149,154	49
84. Hydroxides	25	43
85. Chlorides	22,36,102-104,132	48,42
86. Metal Eutectics		
89. Other	19	41

CONTAINMENT

		Proponents	References
	ABOVEGROUND		
1	High Pressure Tanks		
11	Welded Steel	1	4,5,39,40
12	Prestressed Concrete RV		
13	PCIV	1	4,5,41-45
2	Low Pressure Tanks (Sensible Heat)		
	Single Tank/Thermocline		
21	without packed bed	29	106,112
22	with packed bed	22,24,32	12,13,54,62
23	Drained beds	27	38
	Hot and Cold Tanks		
24	Two tanks without packed bed	21,22,23	16,17,61,62,66
25	More than two w/o packed bed	25,26	6,37,95
3	Low Pressure Tanks (PCM)		
31	PCM in shell/HTF in tubes	42,43,48	25,29,36,132
32	PCM encapsulated into packed bed	42	22,102-104
33	Immiscible Fluid	49,51	149,154
	UNDERGROUND		
4	Steel Tanks		
41	Stress transfer by air	3,8	28,74,75
42	Stress transfer by concrete	2	2,3
5	Unlined Natural Confinement		
51	Aquifers	4,5,6	26,47,108,121,128
	Excavated Caverns	8	156
52	without packed bed		
53	with packed bed	28	10,11,48,68, 76-80
6	Other ?		
7	Not Specified		

Rev. 1-26-78

UTILIZATION

The use of the storage system for utility load management requires a number of "conversions" in state and location, the final one of which is the conversion to electricity. Some plurality of the following conversions are used. These are structured as steps toward Utilization.

U-1. CONVERSION TO ELECTRICITY FROM STEAM
1.1 Increased Steam Flow Through the Main Turbine-Generator
1.11 by decreased extraction for feedwater heating
1.12 by steam addition at the crossover (LP turbine inlet)
1.13 by steam addition at higher temperature and pressure points

1.2 Steam Flow Through Peaking Turbines
1.21 single peaking turbine
1.22 multiple peaking turbines

1.3 Other

U-2. CONVERSION TO ELECTRICITY NOT FROM STEAM

U-3. CONVERSION TO STEAM
3.1 From HTW
3.11 by internal steam generation (in storage container)
3.12 by external evaporators

3.2 From Other Sensible Heat Fluids
3.21 in indirect heat exchangers
3.22 in direct heat exchangers

3.3 From Solids; Direct Heat Exchange

3.4 From Gases or Vapors; Indirect Heat Exchange

3.5 From Latent Heat Fluids
3.51 Liquid/Solid PCM
3.52 Gas/Liquid PCM

3.6 Superheaters

U-4. NON-STEAM HEAT EXCHANGERS
4.1 Sensible/Sensible Heat
4.11 Liquid/Liquid
4.12 Liquid/Solid
4.13 Liquid/Gas

4.2 PCM Materials
4.21 Sensible/PCM
4.22 PCM/PCM

U-5. THERMAL TRANSPORT
5.1 Pipes

5.2 Heat Pipes

5.3 Other

U-6. CONTROLS AND MISCELLANEOUS

APPENDIX C
CONCEPT DEFINITIONS

FOR

CONCEPTUAL DESIGN OF THERMAL ENERGY STORAGE
FOR
NEAR-TERM ELECTRIC UTILITY APPLICATIONS

CONCEPT DEFINITION #1

PROPONENT(S)

Prof. Paul V. Gilli - Graz University of Technology, Austria
George Beckmann - Waagner Biro

References

4-5, 39-45, 117, 141

CHARACTERIZATION

Medium	12,13	HTW 212 to 250°C
Containment	11	Welded steel pressure vessels plus cold condensable storage ~50°C
Source of Heat	21	Extraction steam at feedwater extraction points
Conversion	321,322	Multiple turbines operating at different input pressures

DESCRIPTION

This concept is a baseline configuration, not now the favored concept of the proponents but one of the earliest in their listed references. It features high temperature water as the storage medium, containment in welded steel pressure vessels, source energy from steam extraction points, and multiple peaking turbines on a common shaft, with distinct pressure ranges.

Figure 42 from Reference 45 summarizes the system concept. Steam extracted for feedwater heating at four normal extraction points is partly diverted to a set of steam accumulators. The three lowest steam temperatures are supplied sequentially to each accumulator in the set to increase the temperature and pressure of the water therein in steps minimizing availability loss. The fourth steam source is supplied to a higher pressure accumulator for superheat. Complex valving is needed to supply each steam source to each accumulator in the proper sequence. Controls and instrumentation to monitor this can also be complex.

Prof. Gilli suggests this concept is suitable for welded steel pressure vessels. The sequencing of accumulators during charging and discharging implies a large number of small tanks. Reference 40 shows a "working model" for this concept with 64 tanks of 580 m^3 each.

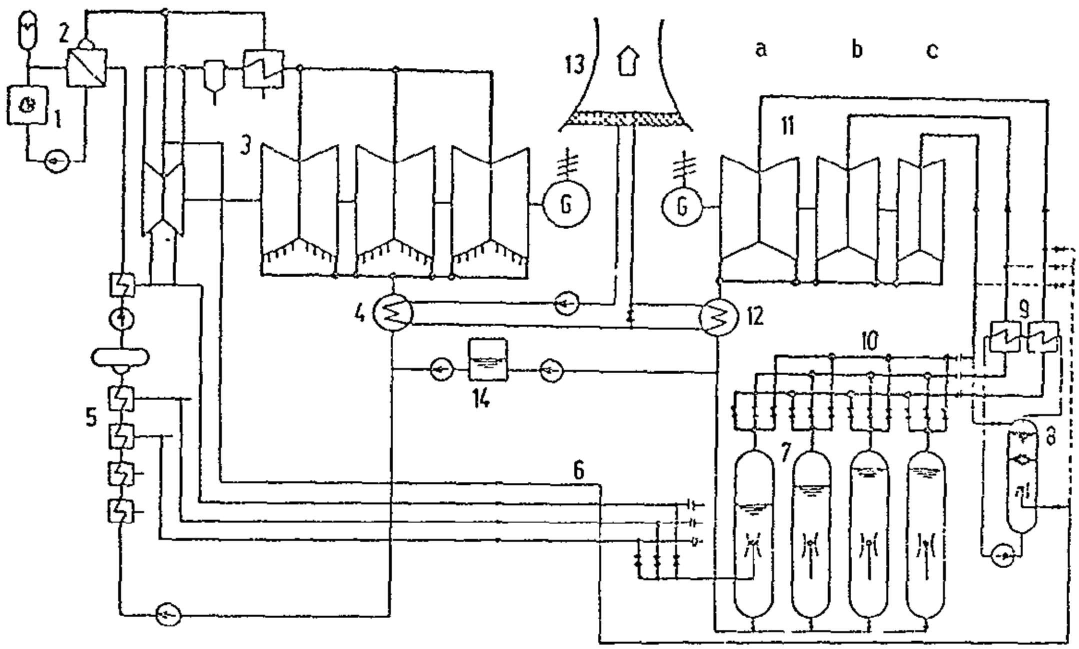


Fig. 42 Flow sheet suitable for the use of welded steel storage vessels, employing varying pressure storage, sequential discharge, separate peak load turbine and multi-pressure condenser

1 Reactor (PWR)
2 Steam Generator
3 Main (base load) turbine
4 Main condenser
5 Feed heater train
6 Charge line
7 Main accumulators
8 Superheat accumulator
9 Superheater
10 Discharge steam lines
11 Peak load turbine
12 Peak load condenser
13 Cooling tower
14 Condensate storage

Source: Reference 45.

During discharge of each accumulator, steam is generated internally by reducing the pressure at the outlet. Three peaking turbines (11 a, b, and c) on a common shaft are designed for inlet pressures of 1 MPa, 0.5 and 0 18 MPa (145, 73, and 26 psia) and condenser pressure of ~0.012 MPa (~1.7 psia). As steam is generated in an accumulator the pressure continues to decrease. By throttling, the discharge steam is reduced to the next lowest turbine inlet pressure; each turbine operates at constant inlet pressure. As in charging, the accumulators are sequenced by valves to the next lowest pressure turbine when the steam pressure falls to or below the design turbine inlet pressure.

As shown, separate double-flow turbines for high, medium, and low pressure steam are provided. They are designed to be simple, rugged, and to accommodate the rapid thermal expansion during frequent starts and stops. No provision for steam bleeds for feedwater heaters or for moisture removal is made. To minimize exhaust wetness, which affects turbine efficiency and life, superheater accumulators (point 8 in the figure) are provided.

The superheater accumulators as shown are of the displacement type. They are charged with extraction steam at ~2 MPa. During discharge, high temperature water (HTW) from the top passes through two heat exchangers in the turbine inlet lines to the two highest pressure turbines. The HTW at reduced temperature is reinjected at the bottom of the accumulator, forming a rising thermocline. Pressure and temperature of the output are more nearly constant than in the variable pressure type.

As the water volume in the accumulators (7) is greater when charged than when discharged, tanks for condensate storage (14) during the discharged period must be provided, with roughly one-fourth the capacity of the accumulators but at roughly ambient pressure.

PERFORMANCE

State Points

Charge line 1:	0.5 MPa, 150°C V
2:	1.0 MPa, 180°C V
3:	2.0 MPa, 212°C V
Accumulators:	2.0 $\longrightarrow$ 0.2 MPa
	212 $\longrightarrow$ 120°C
Superheater charge line:	4.8 MPa, 260°C
discharge :	4.8 MPa, 260°C
reinjection:	4.8 MPa, 175°C
Turbine Inlets a:	1.07 MPa, 245°C
b:	0.49 MPa, 179°C
c:	0.14 MPa, 119°C
Condenser:	0.012 MPa, 50°C

Storage Efficiency

0.5 - 0.75 (Reference 45, p 81)

CONCEPT DEFINITION — VARIANT 1.1

PROPONENTS

Prof. Paul V. Gilli - Graz University of Technology, Austria
George Beckmann - Waagner Biro

References

4-5, 39-45, 117, 141

CHARACTERIZATION

Medium	11,12,13	HTW 120 to 260°C
Containment	11	Welded steel pressure vessels plus cold condensable storage ~50°C
Source of Heat	11	Extraction of feedwater before HP pump for main storage; feedwater at boiler inlet and cold reheat; steam is used for superheat storage
Conversion	321,322	Multiple turbines operating at different input pressures

DESCRIPTION

Much of the configuration for this concept, as shown on Figure 45 of Reference 45, is similar to Concept Definition 1. The storage pressure vessels instead of being variable pressure accumulators, with internal steam generation, are displacement accumulators with external steam generation. A displacement accumulator is always filled with liquid. During charging, HTW is injected at the top and cold water is withdrawn from the bottom. The boundary between them, a thermocline, moves downward but stays reasonably sharp.

During discharge, HTW is withdrawn from the top and passed sequentially through three flash evaporators used as external steam generators. In each of these, the HTW is throttled to a reduced pressure at which a fraction of the water is transformed to saturated steam, and the remainder is water at saturation temperatures. This water goes to the throttle for the lower pressure steam generators. From the lowest pressure flash evaporator the water at a reduced temperature is returned to the bottom of the displacement accumulators where a rising thermocline is formed. The total mass of water stored in the accumulators differs somewhat between the fully charged and discharged conditions because of the net thermal expansion of the water and the containment. Condensate storage (14) provides a reservoir for this differential, which is much smaller than needed in Concept Definition 1.

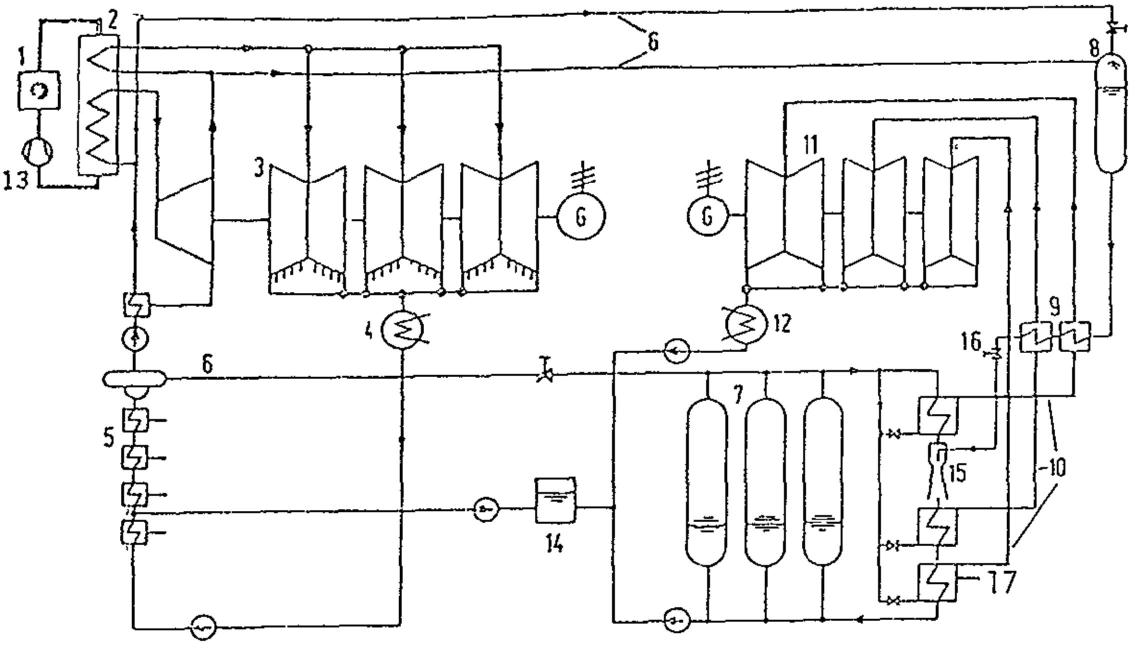


Fig. 45 Flow sheet suitable for the use of welded steel storage vessel, employing displacement-type storage, external steam generation and separate peak-load turbine

1 Reactor (HTR)
2 Steam Generator
3 Main (base load) turbine
4 Main condenser
5 Feed heater train
6 Charge line
7 Main accumulators
8 Superheat accumulator
9 Superheater
10 Discharge steam lines
11 Peak load turbine
12 Peak load condenser
13 Helium blower
14 Condensate storage
15 Jet pump
16 Start-up valve
17 Steam generator

Source: Reference 45.

Steam leaves the three steam generators at three pressures. Each is at a constant pressure and needs no further throttling. The top two are superheated, partly by heat exchange from a separate HTW flow passed sequentially through the steam generators and partly by heat exchangers fed by an expansion accumulator (8). An expansion accumulator maintains an almost constant temperature and pressure during discharge by withdrawal of HTW from the bottom and increasing the size of the steam cushion by evaporation of a small fraction of the water. The superheater is charged by injecting both HTW at the final feedwater temperature, and enough cold reheat steam to fill the accumulator at the desired temperature and pressure.

The figure shown is for a gas-cooled HTR. The cold reheat steam is at an adequate pressure and temperature to charge the superheat accumulator to 260°C. The same storage system configuration could be used for an LWR but the source of steam for this accumulator would have to be the main steam supply, rather than cold or hot reheat.

Proponents note as advantages over Concept Definition 1 that this concept does not require the sequential valving of groups of three different charge lines and to three different discharge lines. A recirculation pump is usually needed for displacement accumulators. In this concept the need is eliminated by using the pressure energy of the HTW from the superheaters in a jet pump. This also contributes to the needed condensate storage at 14. The cost and complexity of the valving in Concept Definition 1 must be traded off with the added cost of the evaporators.

CONCEPT DEFINITION — VARIANT 1.2

PROPONENT(S)

Prof. Paul V. Gilli - Graz University of Technology, Austria
George Beckmann - Waagner Biro
F. Schilling - Siempelkamp Giesserei KG, Krefeld, FRG

References

4-5, 39-45, 117, 141, 148

CHARACTERIZATION

Medium	13, 12	HTW at 250-260°C
Containment	13	PCIV main, steel cold storage
Source of Heat	12 & 26 or 24	FWH + steam refills accumulator
Utilization	1.22, 3.12	Three cascaded evaporators

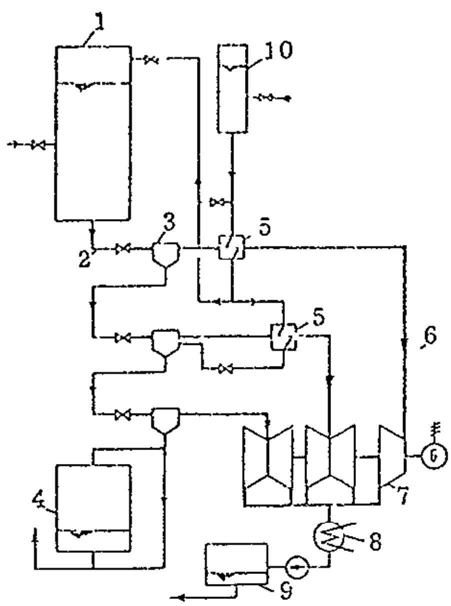
DESCRIPTION

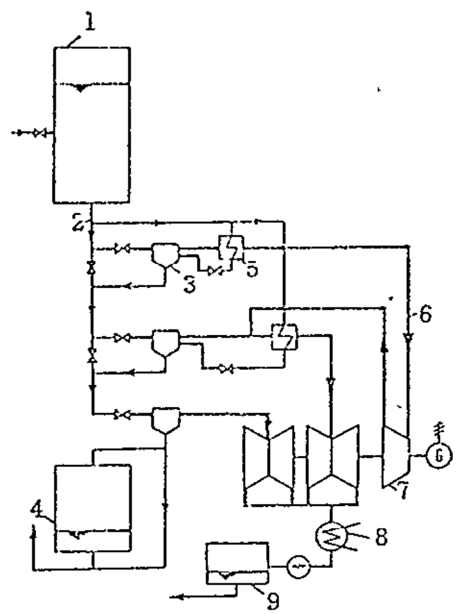
Concept Definitions 1.0 and 1.1 included three basic modes of using a steam accumulator (HTW storage):

- Variable Pressure — Internal steam generation - C 1.0
- Displacement — Both HTW and colder water/thermocline - C 1.1
- Expansion — Constant pressure steam cushion - C 1.1 superheat

All were considered to be welded steel tanks. This concept describes two variants using only expansion type accumulators. It also introduces the mode of containment preferred by the proponents, the prestressed cast iron vessel (PCIV). Figures 46 and 47 of Reference 45 are combined.

The concept of the PCIV is that it can be made in much larger sizes for high pressures than welded steel tanks, with lower cost, lower losses, easier transport and assembly, and improved safety. It could be applied in all three accumulator modes, and may be considered as subvariants of Concepts 1.0 and 1.1. However, the variable pressure mode as used in Concept 1.1 with the requirement for sequential valving during charge and discharging, requires a number of vessels preferably much greater than three, so loses the cost advantage of large size PCIV unless very large storage volumes are required. The displacement mode,





Flow sheets suitable for the use of PCIV, employing expansion-type steam storage, with ______________, and a separate peak-load turbine

Fig. 46 ...superheat storage vessel

Fig 47 ...superheating by means of branched-off stored hot water...

1 Expansion-type accumulator
2 Water discharge line
3 Flash evaporators
4 Cold storage
5 Superheater
6 Steam lines
7 Peak-load turbine
8 Condenser
9 Condensate storage
10 Superheat accumulator

Source Reference 45.

with a vertical temperature distribution including a sharp thermocline poses the problem for thick walled PCIV of thermal stresses near the thermocline. The proponents in most recent concepts and flow diagrams include the expansion mode accumulator.

In both Figures 46 and 47, the mode of charging is assumed to be that used in the superheat accumulator in Concept 1.1. In an expansion accumulator the steam cushion may expand from say 5 percent to 95-100 percent of the storage volume. Replacement is principally with HTW at nearly the desired temperature, with a supplement of steam injection at a higher pressure than desired, which by condensation restores the desired temperature, pressure and steam cushion size. As indicated in Concept 1.1, for the superheat accumulator the highest temperature feedwater plus cold reheat steam for a fossil plant and hot reheat steam for the nuclear plant meet the requirements. For the main accumulators either the same feedwater temperature or one before the last boiler feed pump may be used. Cold reheat steam is probably adequate for both the fossil and nuclear applications.

Figures 46 and 47 both show three stages of flash evaporators to feed three parallel turbine sections at different pressure levels. They differ in the means of superheating. The first has a separate superheat accumulator. HTW from it passes sequentially through two heat exchangers to superheat the HP and MP steam flows. The HTW then joins the water flow to the LP evaporator. In Figure 47 the superheaters in the HP and MP steam flows are fed by HTW from the main accumulator (separately, not sequentially). Another flow option is illustrated in Figure 47 by the design of the HP turbine to supply steam output at the pressure level of the MP turbine instead of expanding all the way to condenser pressure. This changes the power and cost distribution among the three turbine casings.

One property of expansion accumulators is a large swing in the size of the steam cushion. A separate cold storage tank of welded steel (4) must be provided with about half the volume as the main accumulator but at pressure near atmospheric (eg, 120°C). No circulation pumps are required in the storage loops of this concept. Required sizes and pressures of vessels required versus simplicity of operation and the needed auxiliaries such as valving, controls, and pumps are cost tradeoffs to be considered.

CONCEPT DEFINITION – VARIANT 1.3

PROPONENT(S)

Prof. Paul V. Gilli - Graz University of Technology, Austria
George Beckmann - Waagner Biro
F.E. Schilling - Siempelkamp Giesserei KG, Krefeld FRG

References

4-5, 39-45, 117, 141, 148, 175, 188, 189, 192, 209

CHARACTERIZATION

Medium	13	HTW at 250°C
Containment	11	PCIV
Source of Heat	26,12	Live steam and hot feedwater
Utilization	1.21,3.12	Single evaporator feeds peaking turbine and hot feedwater

DESCRIPTION

The capabilities of the PCIV are claimed to be higher in pressure (and temperature) than can be considered for welded steel tanks of large sizes. To take full advantage of this, the proponents describe (Figures 49-51 in Reference 45) several closely related concepts applicable to fossil (coal) plants with main steam supply of 540°C and 17 to 24 MPa. Expansion accumulator(s) operate at a charged pressure between the main steam and the cold reheat (8 MPa) so that a one-stage flash evaporator (9) can supply additional steam flow to the reheater, IP and LP turbines during peaking. The main IP and LP turbine can be sized to provide the added capacity or a separate IP and LP turbine and condenser can be provided at 10 and 11.

The expansion accumulator (2) is charged by a mixture of feedwater and throttled main steam supply. During discharge the water and steam pressure and temperature can be maintained steady by small continuing injection of live steam at the top port. The water output of the flash evaporator is reinjected into the feedwater loop by a HP feed pump. Conservation of total feedwater volume requires that feedwater tank (7) be sized to accept the change in liquid volume in the accumulator between fully charged and discharged condition.

1 Heat source
2 Expansion-type PCIV
3 Main turbine, HP
4 " " , IP
5 " " , LP
6 Main condenser
7 Feed water tank (cold storage)
8 Feed water heater
9 Flash evaporator
10 Peak load turbine, HP
11 Peak load turbine, LP
12 Peak load turbine, condenser

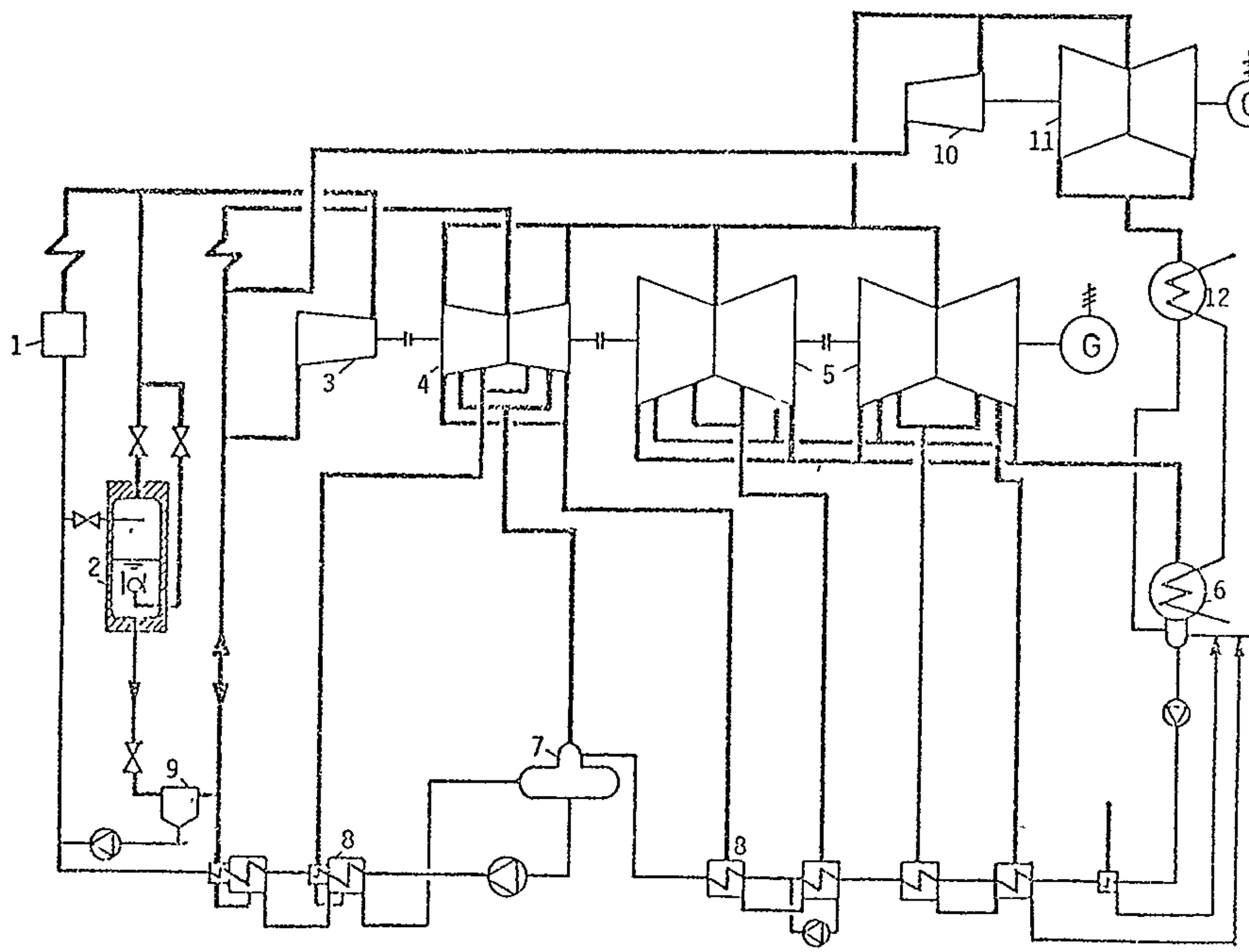


Fig. 49 Expansion-type feed water and steam storage with separate peak load turbine

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CONCEPT DEFINITION #2

PROPONENT(S)

R&D Associates - J. Dooley
S. Ridgway

References

28, 74, 75, 81

CHARACTERIZATION

Medium	13	HTW from 290 to 360°C
Containment	42	Steel tank in underground cavity. Stress transfer to rock by concrete.
Source of Heat	26	Prime Steam
Utilization	1.2	Steam used in peaking turbine(s)

DESCRIPTION

This concept features high temperature water as the storage medium, contained in underground cavities. Source of energy is from prime steam. Utilization of energy is by generating steam in cavity and feeding through peaking turbines.

Figure 1 from Reference 81 shows a schematic diagram of the concept. The underground cavity has a thin (1/2-inch) welded-steel liner, with special high-temperature, high-strength concrete filling the space (about 1 foot thick) between the liner and cavity wall to transfer stresses to the rock as well as to provide thermal insulation. The cavity is operated as a variable-pressure steam accumulator (see Concept Definition #1), charged with prime steam up to temperatures as high as 360°C. On discharge, steam is generated in the cavity and fed directly to separate peaking turbines. As the cavity discharges the steam temperature and pressure decrease, resulting in a decreasing output from the peaking unit. In order to keep thermal stressing of the cavity liner within "conservative" values the temperature swing is limited to 40°C, which results in limiting the discharge to between 15 and 40 percent of the cavity volume, depending on the initial temperature. The specific energy storage (defined as actual work out of turbine/cavity volume) is between 18 and 21 kWh/m^3, with a claimed turnaround efficiency of 85 percent. Direct costs for storage cavity are estimated at 160 to 177 \$/m^3 in the sizes recommended.

Reference 75 mentions that proponents have also considered operating the cavity as a constant-pressure displacement accumulator, but considered it less desirable. No further details are given.

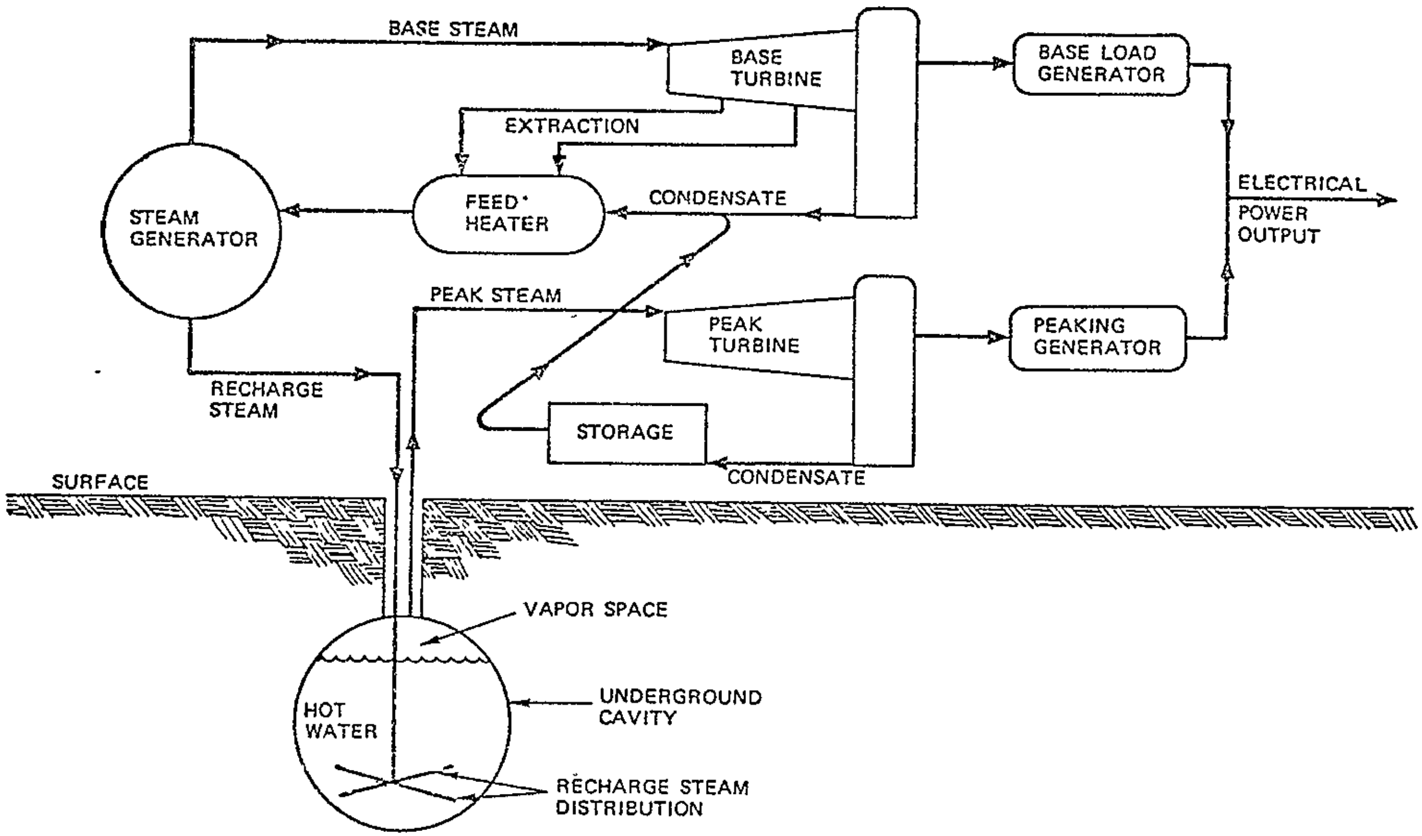

Figure 1. Thermal Energy Storage System Schematic.

CONCEPT DEFINITION #3

PROPONENT(S)

Ontario Hydro - A.G. Barnstaple
J.J. Kirby
J.E. Wilson

References

2, 3

CHARACTERIZATION

Medium	12	HTW up to 180°C (350°F)
Containment	41	Steel tanks in underground cavern. Stress transfer to rock by compressed air.
Source of Heat	11	Heated feedwater
Utilization	1.11	Hot feedwater reduces extraction for feedwater heating, primarily at crossover from HP to LP turbine.

DESCRIPTION

This concept features storage of heated feedwater in underground tanks. The energy is utilized by using the stored water to partially supply the feedwater requirements, thereby reducing steam extracted for feedwater heating.

Figure 5.2.1 from Reference 3 summarizes the system concept and shows the heat balance for normal operation (ie storage inactive). The storage system is a constant-pressure displacement accumulator (see Concept Definition - Variant 1.1) consisting of three insulated steel tanks in a cavern about 150 m underground. The air in the cavern is pressurized and cooled, allowing a thin-wall tank designed only to contain the static heat of the stored water plus a small allowance for imbalances. An open-surface pressure-balancing reservoir keeps the stored water in contact with cavern pressure.

The accumulator is charged by pumping heated feedwater (≈180°C) into the top and colder water (≈95°C) out the bottom and into the final three stages of the feedwater heater chain. On discharge stored

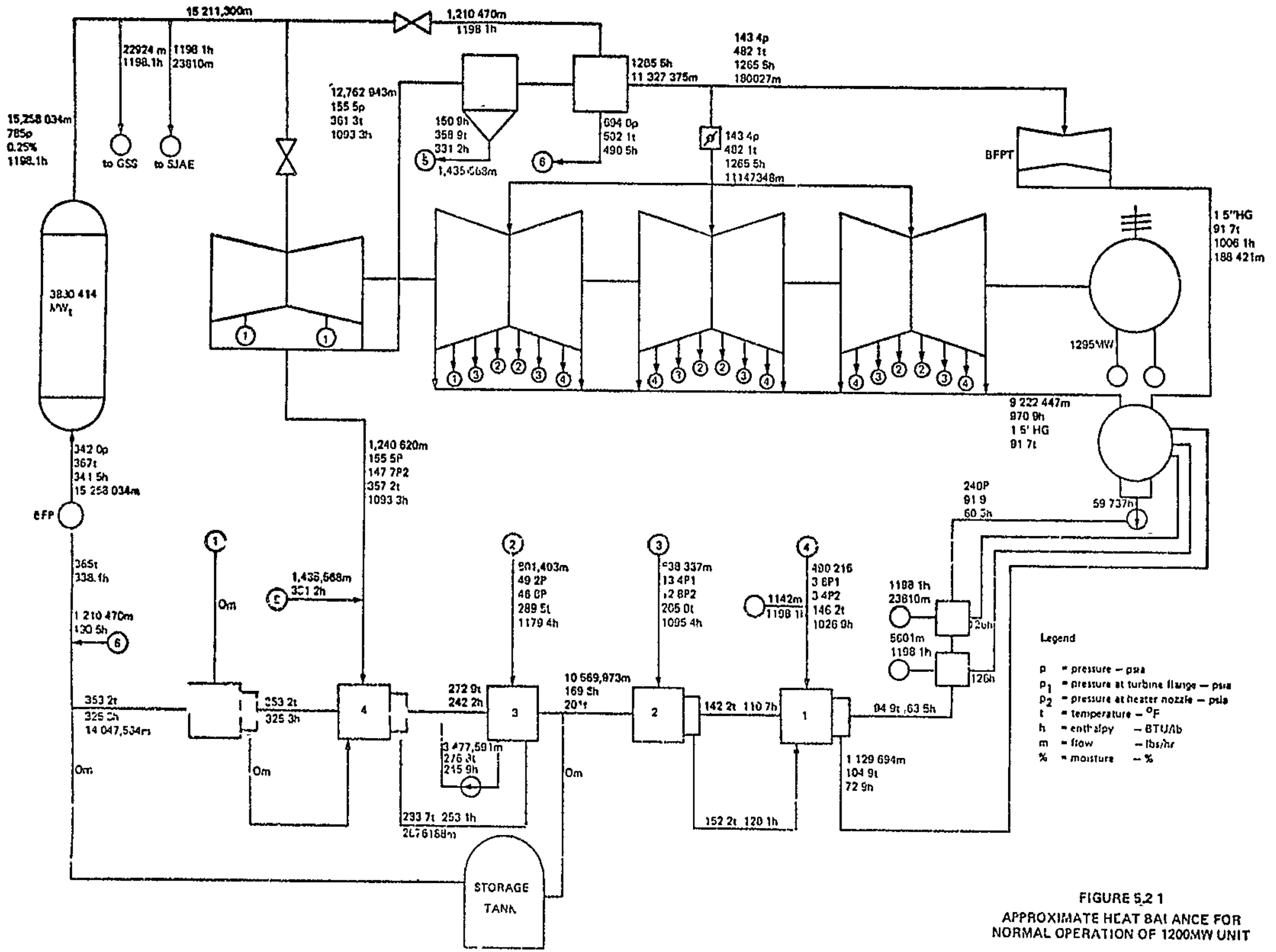

FIGURE 5.2 1
APPROXIMATE HEAT BALANCE FOR NORMAL OPERATION OF 1200MW UNIT

hot water is pumped from the top of the tank to the output of feedwater heater chain and cold water from the feedwater loop pumped into the bottom.

Proponents claim the storage (turnaround) efficiency "is likely to be above 80 percent," based on an estimated cavern leakage rate of 2 percent per day. The basic cycle examined is that of a CANDU-PHW 1200 MW_e unit, with modifications to accommodate feedwater storage. For this unit the peak output is limited to about 6.5 percent above normal operation. The specific energy storage is about 14 kWh/m^3, with storage-related direct costs estimated at 210 - 280 $\$/m^3$ in 1976 dollars, or 15 to 20 \$/kWh.

A minor variant of this concept stores a supply of hot water condensed from prime steam, for use in reheating as well as feedwater supply. Since this would not supply all the necessary feedwater, additional feedwater storage is required. This scheme provides a peak output about 13 percent above normal operation, but is not favored due to the higher cost of storing water at temperatures suitable for reheat — with only a slight increase in output.

Proponents also note that other cycles may be able to achieve up to 25 percent peaking capability, with suitable redesign of the turbine. However, the low coolant temperature of the CANDU pressure tube design and the high temperature rise in the reactor, when combined with pinch-point limitations, dictate a relatively low feedwater temperature and limit the peaking capability.

CONCEPT DEFINITION — VARIANT 3.1

PROPONENT(S)

Ontario Hydro - A.G. Barnstaple
J.J. Kirby
J.E. Wilson

References

2, 3

CHARACTERIZATION

Medium	13	HTW at about 265°C (510°F)
Containment	41	Steel tanks in underground cavern. Stress transfer to rock by compressed air.
Source of Heat	26	Prime steam from main boiler
Utilization	1.22	Flashed steam powering separate peaking turbines

DESCRIPTION

This concept features storage of high temperature water in underground tanks. Stored energy is obtained by condensing prime steam and is utilized by flashing to steam which powers multiple peaking turbines on a common shaft.

Figure 6.2-1 from Reference 3 summarizes the system concept. The storage system is a constant-pressure displacement accumulator (similar to that described in Concept Definition #3) consisting of six to eight insulated steel tanks in a cavern about 2000 m underground. The air in the cavern is pressurized (to about 9 MPa) and cooled, permitting a thin-wall tank designed only to contain the static head of the stored water, plus a small allowance for imbalances. An open-surface pressure balancing reservoir keeps the stored water in contact with cavern pressure.

The accumulator is charged by pumping cold water from the bottoms of the tanks to a spray condenser fed from the prime steam supply (5.4 MPa, saturated). Heated water ($\approx$265°C) from the spray condenser is pumped into the top of the accumulator and excess cold water stored in the main boiler feedwater storage tank. During discharge the stored hot water is pumped from the top of the tanks and passed sequentially through three external flash evaporators, each supplying steam to

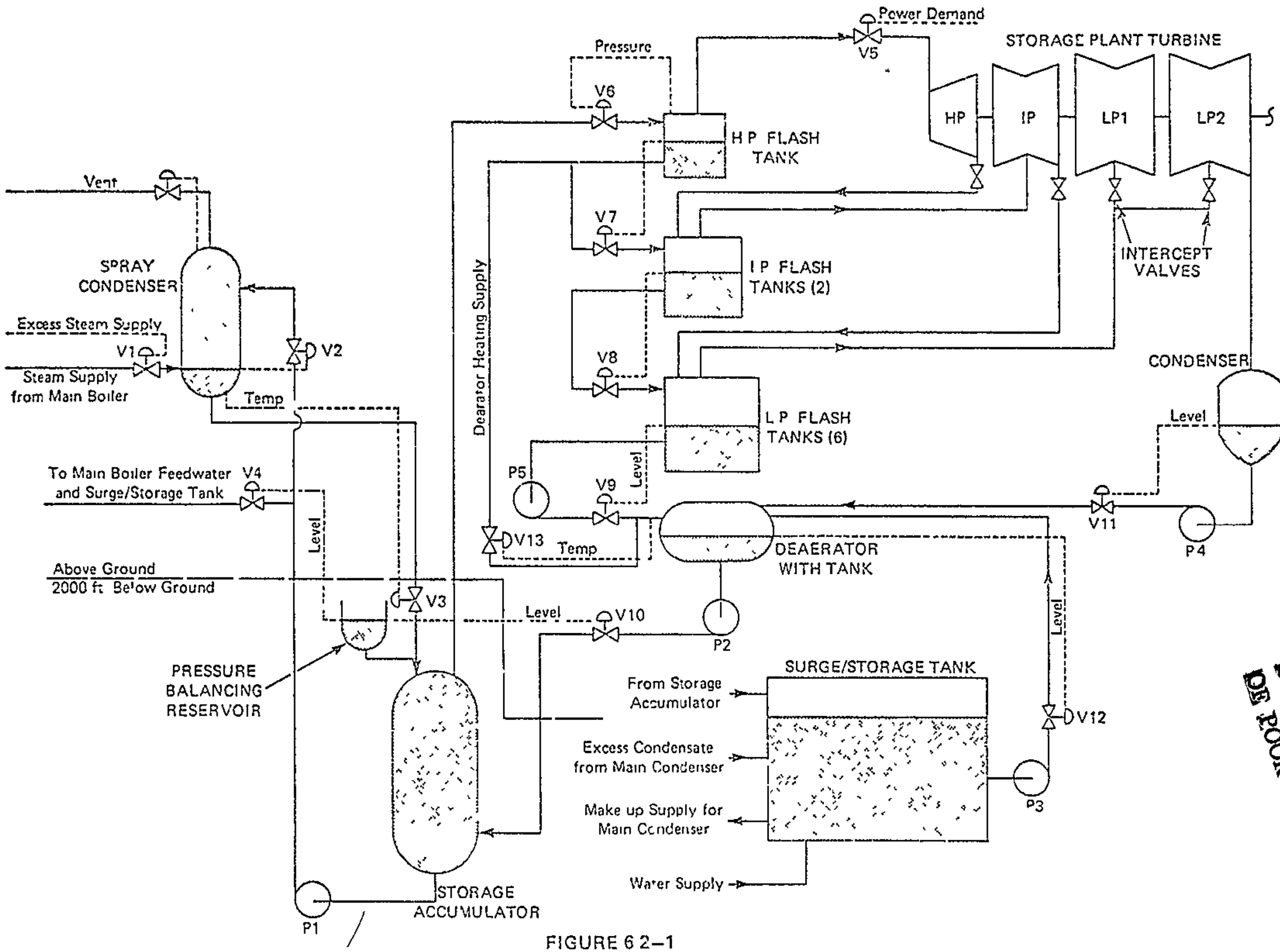

FIGURE 6 2–1
CONSTANT PRESSURE STEAM/WATER
STORAGE PLANT FOR 1200 MWe, PHW

separate peaking turbines operating over different pressure ranges. Cold water from the low pressure evaporator and the condenser is pumped into the bottom of the tanks after deaeration, and excess water is stored in a separate surge/storage tank.

Proponents claim storage (turnaround) efficiencies between 75 and 80 percent, depending on the ratio of charging to discharging times, based on a cavern air leakage of 2 percent. The specific energy storage (actual work out of turbine/storage volume) ranges from 32 to 34 kWh/m^3 for the various charge/discharge ratios analyzed. Estimated direct cost of storage-related equipment ranges from 400 to 460 $\$/m^3$ in 1976 dollars, resulting in a specific storage cost of 11.90 to 14.30 \$/kWh.

CONCEPT DEFINITION #4

PROPONENT(S)

University of Houston - R.E. Collins
Subsurface, Inc. - K.E. Davis

References

26, 47

CHARACTERIZATION

Medium	13	HTW up to 340°C (650°F)
Containment	51	Saline aquifers ≈5000 ft deep
Source of Heat		Not defined
Utilization		Not defined

DESCRIPTION

This concept features HTW as the storage medium contained in deep saline aquifers. It is essentially a storage concept for use in solar electric power systems, but no specific system description is given. However, the operating temperatures proposed would make it suitable for generating steam to run turbines, as in Concept Definition - Variant 3.1.

The storage system is charged by pumping hot water (340°C) into an aquifer, approximately 1500 m deep in order to provide sufficient hydrostatic pressure to prevent flashing of the water. Heat is stored in some of the water as well as in the permeable rock formation of the aquifer. On discharge the water is pumped out of the aquifer. For large storage systems the thermal losses are estimated to be less than 1 percent per day. The proponents recognize that mineral scale deposition in the aquifer (and in any heat exchangers exposed to the HTW) is a serious problem with water at these elevated temperatures. For that reason this concept is not now favored.

CONCEPT DEFINITION #5

PROPONENT(S)

General Electric-TEMPO — C.F. Meyer

References

108, 121

CHARACTERIZATION

Medium	12	HTW up to ≈200°C (390°F)
Containment	51	Confined aquifers >150 m deep
Source of Heat		Feedwater heating
Utilization		Reduced extraction for FWH

DESCRIPTION

This concept features HTW as the storage medium contained in confined aquifers. It is essentially a method providing long-term storage of large amounts of heat to facilitate the use of total energy systems. However, the operating temperature range proposed makes it suitable for use as a feedwater storage system as in Concept Definition #3.

Figure 9 from Reference 121 illustrates the basic module of this storage concept. In order to supply the HTW to be stored and to dispose of the water withdrawn from storage, two wells — a doublet — are used. They are spaced farther apart than the radius for the maximum volume of storage. Both tap the same aquifer which is confined top and bottom by impervious layers. To charge the system water is cycled from the right well to the left well. A heat exchanger keeps the groundwater separate from the high quality boiler feedwater. When heat is needed from storage, water is withdrawn from the left well and injected into the right well, which will be warm compared to native groundwater.

In order to prevent the water from flashing to steam, the hydrostatic head must be higher than the saturation pressure, requiring moderately deep aquifers. For example, HTW at 200°C (saturation pressure ≈1.7 MPa), will require aquifers at least 150 m deep. Although mineral scale deposition is expected to be a problem, at the moderate temperatures involved proponents conclude that it should be within current technological capabilities. Direct capital costs for a module are power related, rather than total energy related, because the storage volume of the aquifer is essentially unlimited. A module capable

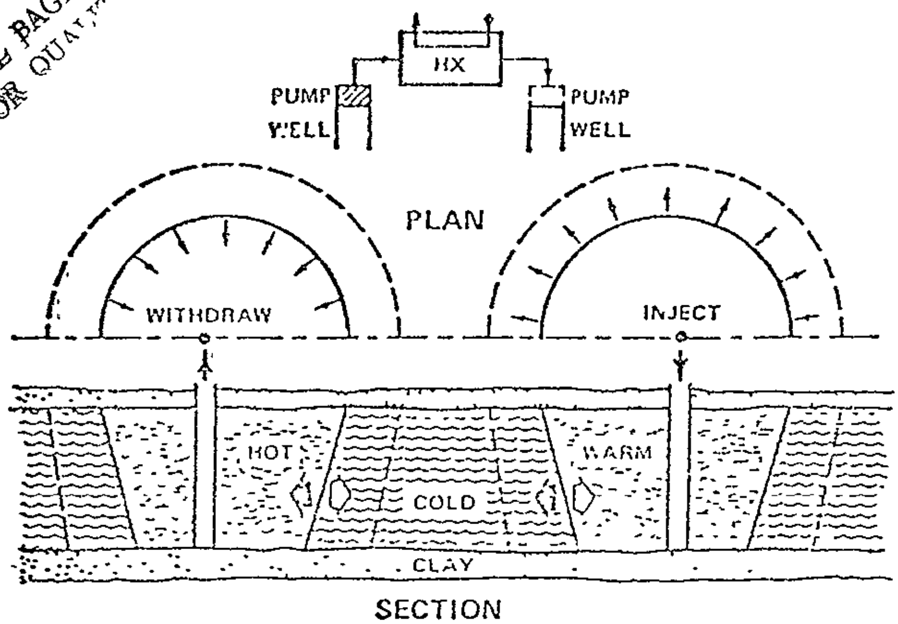

Figure 9. A doublet Heat Storage Well.

of delivering 200°C water at a rate of about 160 m^3/hr (700 gal/min) is estimated to cost \$350,000 to \$740,000 in 1974 dollars. If used as a substitute for the feedwater storage in Concept Definition #3, this flow rate would produce about 2.5 MW additional electrical output. Assuming an 8-hour discharge at constant rate results in a cost of about 18 to 37 \$/kWh in 1974 dollars. A well field of 20-30 well pairs would be used for production of 50-75 MW electric.

The concept would be more competitive for seasonal than for daily load leveling. For the weekly cycle, economic analysis is required.

A related concept of application is to store HTW during the night hours in all seasons and all day long in the non-peak seasons, thereby reducing the turbine generator electric output to 80 percent of peak capacity during off-peak hours. The stored HTW would supply a district heating system serving space-heating loads in the winter season.

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CONCEPT DEFINITION #6

PROPONENT(S)

Ian Glendenning - Central Electricity Generating Board, UK
James O'Hara - R.M. Parsons, Inc.
Philip Chow - T.Y. Lin International
W.L. Greenstreet - ORNL

References

200, 152, 153, 222

CHARACTERIZATION

See Concept Definitions 1 and 3.

DESCRIPTION

Prestressed Concrete Pressure Vessels (PCPV) are an aboveground containment means alternative to the PCIV or steel vessels in Concept 1. There is over 35 years of experience with prestressed concrete structures such as buildings and bridges, in which prestressed tendons assure that the concrete is always in compression for expected loadings. As pressure vessels, secondary containment for nuclear reactors has literature references back to 1964. T.Y. Lin International informs us that Bechtel alone has engineered and/or constructed 59 PCPVs in the U.S. and abroad, and that the total number of vessels (at about 0.4 MPa, 60 psi) completed and under construction in the United States is 210. They report that one for 4 MPa (600 psi) has been completed for a reactor.

Both ORNL and the team of R.M. Parsons, Inc. and T.Y. Lin International have studied conceptual designs for coal gasifier process containment. James O'Hara of R.M. Parsons provided data separating out the direct costs for the PCPV alone (without ancillary process equipment) for several sizes, pressures, and temperatures studied (7 and 14 MPa, ambient to 1650°C). Cost comparisons between PCPV and multiple steel modules had been made in each case; the steel vessels cost 2.5 to 5 times as much per m^3.

Glendenning of CEGB has studied underground compressed air storage, with storing the thermal energy of compression in packed rock beds in an aboveground pressure vessel as a system option. Both PCPV in large sizes (28,000 m^3. 10^6 ft^3) and steel pressure vessels were considered; again.

The basic concept of PCPV construction is the field construction of a reinforced and prestressed thick concrete wall around a thin steel container for thermal storage or other process use. Immediately surrounding the steel container is a moderately thick layer (0.2 - 0.5 m) of high-temperature high-strength concrete, a material costing about five times as much as conventional concrete. This material can withstand high temperatures and thermal cycling duty such as rocket test stands, jet engine pads, etc. The conventional concrete should not be exposed to high temperatures (100 - 250°C limits as mentioned in various sources) so a cooling system of built-in metal fins and water carrying tubes may be needed at the interface between high temperature and conventional concrete.

The conventional concrete is restricted in cracking by conventional reinforcing bars and placed in permanent compression by inclusion of a multiplicity of vertical and perimetrical tendons. While external cable wrapping is proposed by some (ORNL, Reference 200), more recent technology incorporates the cables at various intermediate radii in the concrete, and uses inverted U tendons to apply prestressing both to the cylindrical containment and the hemispherical end caps. As the concrete is poured in layers of several feet per week conduits are incorporated into which the tendons can be threaded.

CONCEPT DEFINITION #8

PROPONENT(S)

A.B. Atomenergi - P.H. Margen

References

60, 156

CHARACTERIZATION

Medium	12	HTW up to $\approx$ 220°C
Containment	41	Steel tanks in underground cavern. Stress transfer to rock by compressed air.
Source of Heat	11	Heated feedwater
Utilization	1.11	Heated feedwater reduces extraction for feedwater heating

DESCRIPTION

This concept features storage of heated feedwater in steel tanks located in a pressurized underground cavern. The stored energy is utilized by supplying heated feedwater, thereby eliminating the need for extraction steam to the high pressure feedwater heaters.

Figure 1 from Reference 60 summarizes the system concept. The storage system is a constant-pressure displacement accumulator consisting of two insulated steel tanks in a cavern about 60 m underground. The air in the cavern is pressurized and cooled, permitting use of a thin-wall ($\approx$2.5 cm) tank designed only to contain the static head of the stored water plus an allowance for imbalances. An open-surface pressure-balancing reservoir keeps the stored water in contact with cavern pressure.

The accumulator is charged by pumping cold water out the bottom of the tanks, through the three high-pressure feedwater heaters (thereby increasing extraction steam flow to these heaters), and into the top of the tank. On discharge the feedwater flow to the high-pressure heaters is shunted to the bottom of the tanks and hot water from the top is supplied to the boiler, thus eliminating extraction steam to the high-pressure heaters. Two methods are suggested to provide for the volume change of the water as the accumulator is charged and discharged. One method utilizes a small steam cushion at the top of the tanks, fed with extraction steam to maintain a constant pressure. For

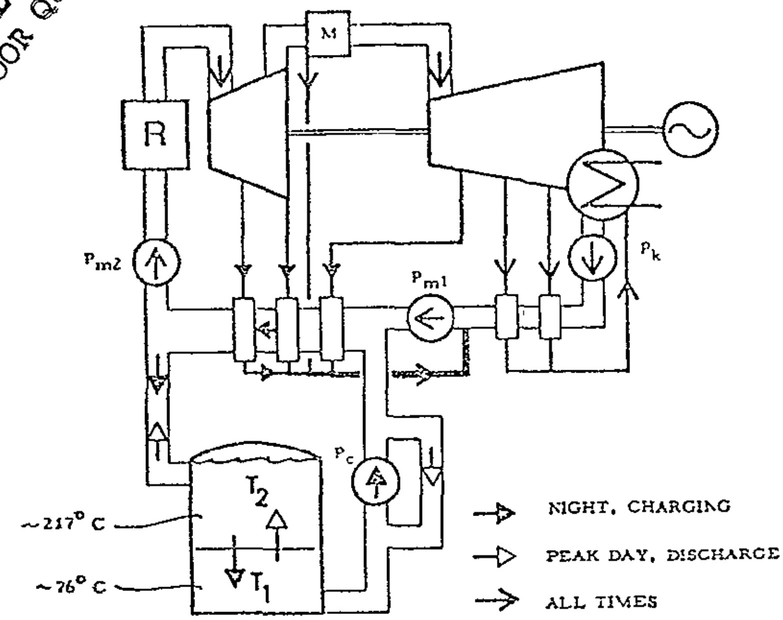


FIG.1. Principle of feedwater storage.

the alternative method the accumulator is maintained full of water and the expansion volume provided by an expansion tank on the surface.

For the cycle described the proponent estimates a peak turbine output about 25 percent above normal (ie no storage), with suitable redesign of the turbines and condenser. Low-pressure turbine exhaust area would be increased about 38 percent above conventional designs, or a separate low-pressure turbine provided, to handle the increased steam flow during peaking. The high-pressure feedwater heaters and the associated steam bleed points must be designed for larger flows during the charge cycle.

Proponent estimates the specific energy storage for this concept at 35 kWh/m^3 and the direct capital cost of storage-related equipment at 52 \$/m^3 in 1971 dollars. This results in about 1.50 \$/kWh.

CONCEPT DEFINITION #21

PROPONENT

Exxon - R.P. Cahn, E.W. Nicholson

References

16, 17, 66

CHARACTERIZATION

Medium	211	Oil (Caloria HT43), 38-274°C
Containment	23	Two atmospheric pressure tanks, aboveground, without packed bed
Source of Heat	21,26	Extraction steam from FWH points and prime steam
Utilization	1.11	For feedwater heating

DESCRIPTION

This concept describes a method of retaining and using the excess heat generated during periods of low power demand when operating a nuclear reactor or fossil fuel furnace and associated boiler at steady-state conditions. The excess heat is stored as sensible heat in low vapor pressure (LVP) organic material at atmospheric pressure, and is used during peak demand periods for boiler feedwater and interstage steam reheating. The LVP material is stored in a cold oil storage tank at approximately 38°C (100°F) when the TES system is in a discharged state, and is heated to approximately 274°C (525°F) by passage through heat exchangers which are heated by a portion of extraction steam at various levels of expansion as well as a portion of the primary high pressure steam. The heated fluid then flows to a hot oil storage tank for retention until needed.

Since steam turbines can be flexibly operated at partial load by varying either the amount of steam fed or the fraction of steam extracted at various points, low load conditions are met by extracting partially expanded steam and diverting some primary steam to heating the oil. High load conditions are met by curtailing the diversion of primary steam and the extraction of expanded steam with a consequent increase in turbine performance, and during this period feedwater and interstage steam reheating are accomplished by heat exchange with the hot oil.

It is calculated that by storing about 25-35 percent of the heat output of the furnace or nuclear reactor, about 15-20 percent of the

plant's power output can be shifted from low load to high load periods. Certain heavy hydrocarbon oils are usable at temperatures below 343°C (650°F) if kept isolated from the atmosphere to prevent oxidation and, since they have satisfactorily low vapor pressure at the maximum temperature, may be conveniently stored in atmospheric pressure tankage.

The system diagram given in Reference 16 indicates that the major items of equipment required in addition to those of a normal steam plant are the hot and cold oil storage tanks and two heat exchanger trains, one for heating the oil during off-peak periods and a separate one for heating boiler feedwater and interstage steam during on-peak periods.

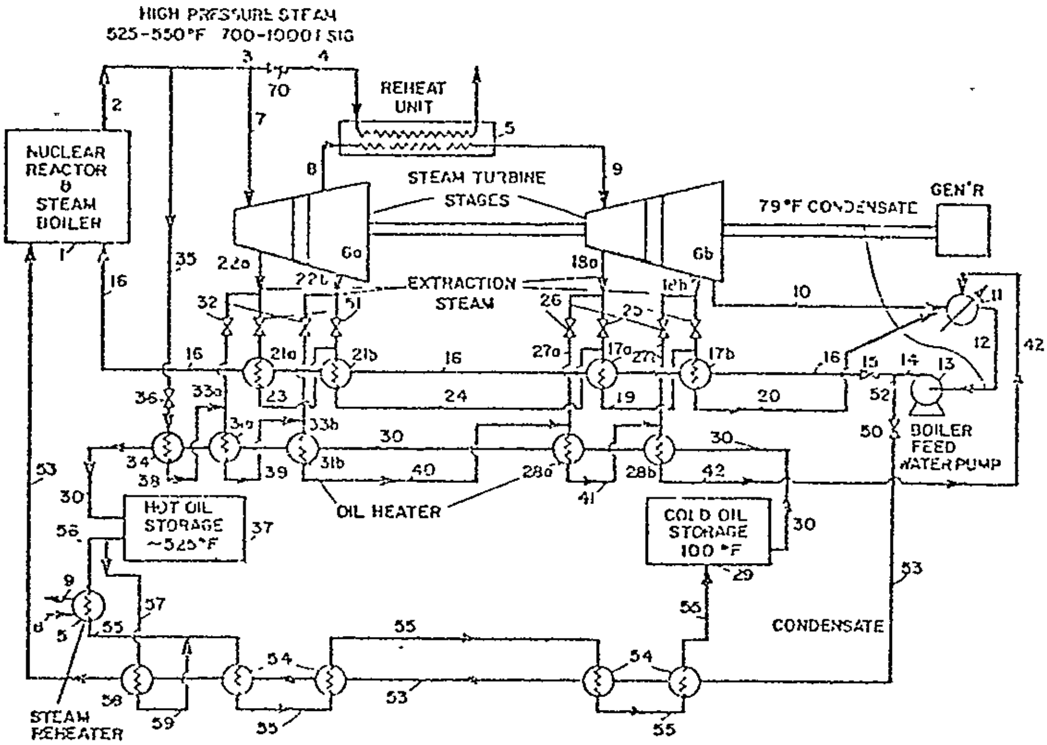
In Reference 17, the proponents point out that there are many alternate arrangements embodying this concept which involve different ways of interconnecting the steam and TES systems, different turbine arrangements including use of a peaking turbine or two half-load turbines, and the concept of using the heat for other heat uses in the steam cycle such as intermediate pressure steam production for turbine drive of auxiliaries.

PERFORMANCE

References 17 and 66 cite the following results of a nuclear power plant design study involving this storage concept.

Type of Power Plant	Nuclear PWR
Primary steam, MPa/°C (psia/°F)	6.9/285 (1000/545)
BFW temperature, °C (°F)	260 (500)
Oil temp., hot/cold, °C (°F)	271/93 (520/200)
Base case capacity	1043 MW_e
Capacity with storage (see note)	1066
Minimum output while charging	713
Maximum output while discharging	1325
Energy charged to storage, 10 hrs	3533 MWh
Energy delivered from storage, 10 hrs	2594
Thermal storage efficiency	73.4%

NOTE: The increased capacity of the modified plant results from the fact that the larger turbine and condenser required for peak operation allows a lower exhaust pressure and consequently more efficient operation.



Source: Patent 3,998,695/Cahn, et al, Reference 16.

CONCEPT DEFINITION — VARIANT #21.1

PROPONENT

Exxon - R.P. Cahn and E.W. Nicholson

References

66

DESCRIPTION

Two variants of the basic concept are briefly discussed in Reference 66; they are storage of hot water coupled with oil storage and use of two turbines.

Water below its normal boiling point, contained in atmospheric pressure tankage, can be used for thermal storage up to about 99°C (210°F). While hot and cold water tanks, pumps, etc would be required, the net effect is more efficient use of the oil storage medium by avoiding the low temperature range where the oil is most viscous and has its lowest specific heat.

Another modification involves storing a nominal amount of boiler feedwater in a high pressure drum at BFW final temperature. This would allow rapid load following and simplified control of the nuclear unit.

Regarding the turbines, it is noted that the difference between the maximum and minimum extraction rates imposes a significant design problem on a single turbine. A two-turbine system may be preferable, with one designed as a peaking unit optimized either for input steam from various takeoffs of the main turbine or for conditions produced by using the stored hot oil for generating steam rather than just BFW heating.

CONCEPT DEFINITION #22

PROPONENT

McDonnell-Douglas Astronautics Co. - R. Hallett, G. Coleman

References

62

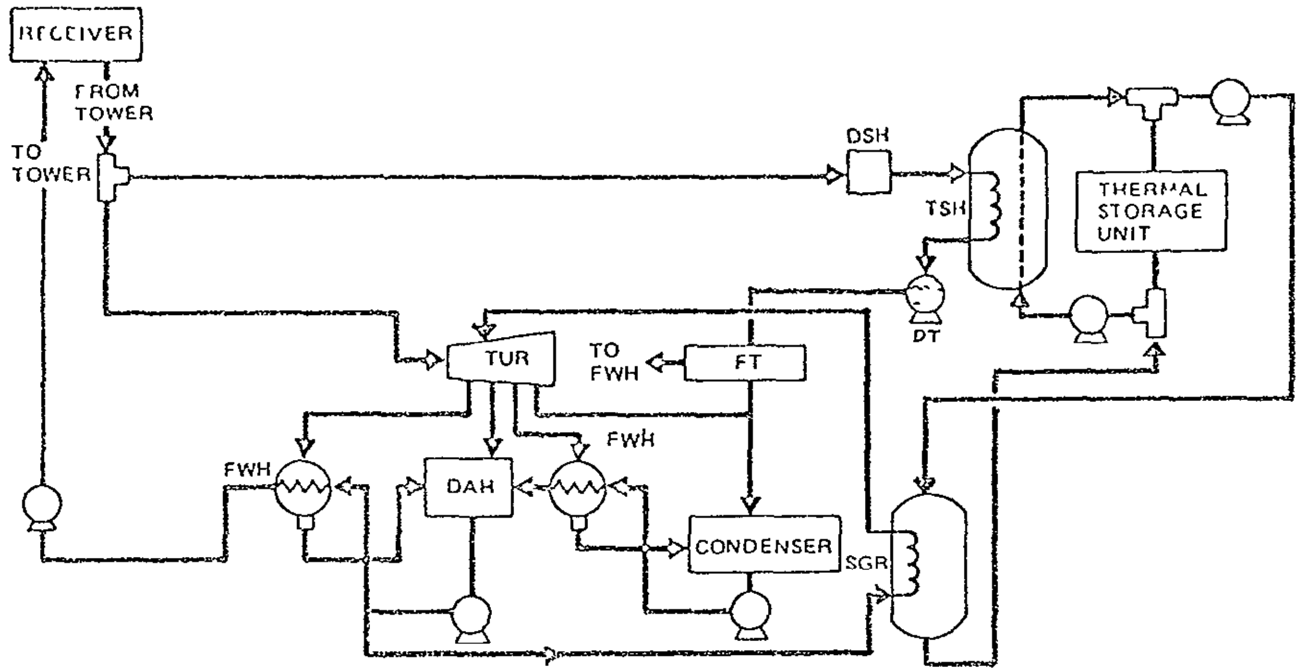
CHARACTERIZATION

Medium	51,52,211	Fixed bed of 1-inch granite gravel and #6 silica sand in Caloria HT43 heat transfer fluid
Containment	22	Aboveground, atmospheric pressure, steel tank operated with a thermocline
Source of Heat	26	Prime steam generated in concentrating solar receiver
Utilization	3.21	Steam generated in indirect heat exchanger admitted to intermediate pressure turbine

DESCRIPTION

This concept, along with numbers 23 and 24, was developed as the thermal storage subsystem of a concentrating solar collector power plant. The function of TES in that context is to smooth out short term variations in insolation (eg, intermittent cloud cover) and to extend plant operation into the hours of darkness. The concept is described here because of the relevance of its TES subsystem to the load following task.

The full system is shown in the accompanying schematic. During periods of adequate insolation, superheated steam from the receiver is supplied in parallel to the turbine/generator (TUR) and, through a desuperheater (DSH), to the thermal storage heater (TSH). The turbine flow comprises a conventional steam cycle with the spent steam exhausting to the condenser and intermediate steam being extracted to feedwater heaters (FWH) and deaerator-heaters (DAH). The thermal storage flow, after transferring its heat to the heat transfer oil pumped from the thermal storage unit, passes through a detemperator (DT) and a flash tank (FT) before rejoining the boiler feedwater return.



When the system is operated on stored energy, hot oil is pumped from storage to the steam generator (SGR) where it vaporizes partially reheated feedwater drawn from the deaerator-heater. The intermediate pressure steam produced is admitted to the turbine at an appropriate point for its conditions.

The system is designed to operate flexibly in a number of modes as dictated by supply (insolation) and load conditions: simultaneous charging and direct power generation, power generation using solar heated steam, power generation using storage heated steam, and simultaneous charging and power generation using storage heated steam to smooth out fluctuations due to intermittent cloud cover.

The thermal storage units consist of a number of identical cylindrical tanks, axis vertical, installed aboveground, containing granite rock and silica sand (in approximately a 2:1 volume ratio) with an 0.25 bed void fraction filled with Caloria HT43 heat transfer oil. During charging, the heated oil at 316°C enters through a manifold at the top of the tank and generates a thermocline as it moves downward heating the rock and sand. Cold oil at 232°C is withdrawn from the bottom manifold and pumped to the thermal storage heater. During discharge, the process is reversed; hot oil is pumped from the top manifold to the steam generator and cold oil is returned to the bottom of the tank. The heat transfer fluid circuit is isolated from the atmosphere, and the tank ullage is kept filled with nitrogen at a small positive pressure. The heat transfer oil is continuously filtered in the main transfer line, and its condition is maintained by periodic removal of a portion for purification by distillation and makeup of losses to polymerization.

For the specific application described in the reference, four tanks are employed, permitting the extraction of 1857 MWht, after 20 hours hold time at a maximum rate of 285 MWt. The tanks are each 27.6 m i.d. and 18.3 m high, with the packed bed standing to a height of 17.1 m and the free oil surface at 316°C at a height of 17.7 m. The tank is fabricated of structural steel, field welded construction, with plate thickness ranging from 44.5 mm at the bottom to 6.35 mm at the top. The conical roof and sites are covered with a 204 mm blanket of fiberglass insulation and a corrugated aluminum weather cover. Each tank contains 20,270 Mg of solids and 1,878 Mg of oil.

The thermal storage steam generator is a 3-stage unit comprising a feedwater heater, boiler, and superheater. Feedwater at 121°C and 2.76 MPa is heated to 230°C for transfer to the boiler where it is converted to saturated steam at the same temperature. Further heating produces steam conditions of 299°C and 2.72 MPa at the superheat output for admission to the turbine.

CONCEPT DEFINITION #23

PROPONENT(S)

Martin-Marietta Corp. - Floyd Blake
Georgia Institute of Technology - S.H. Bomar

References

61

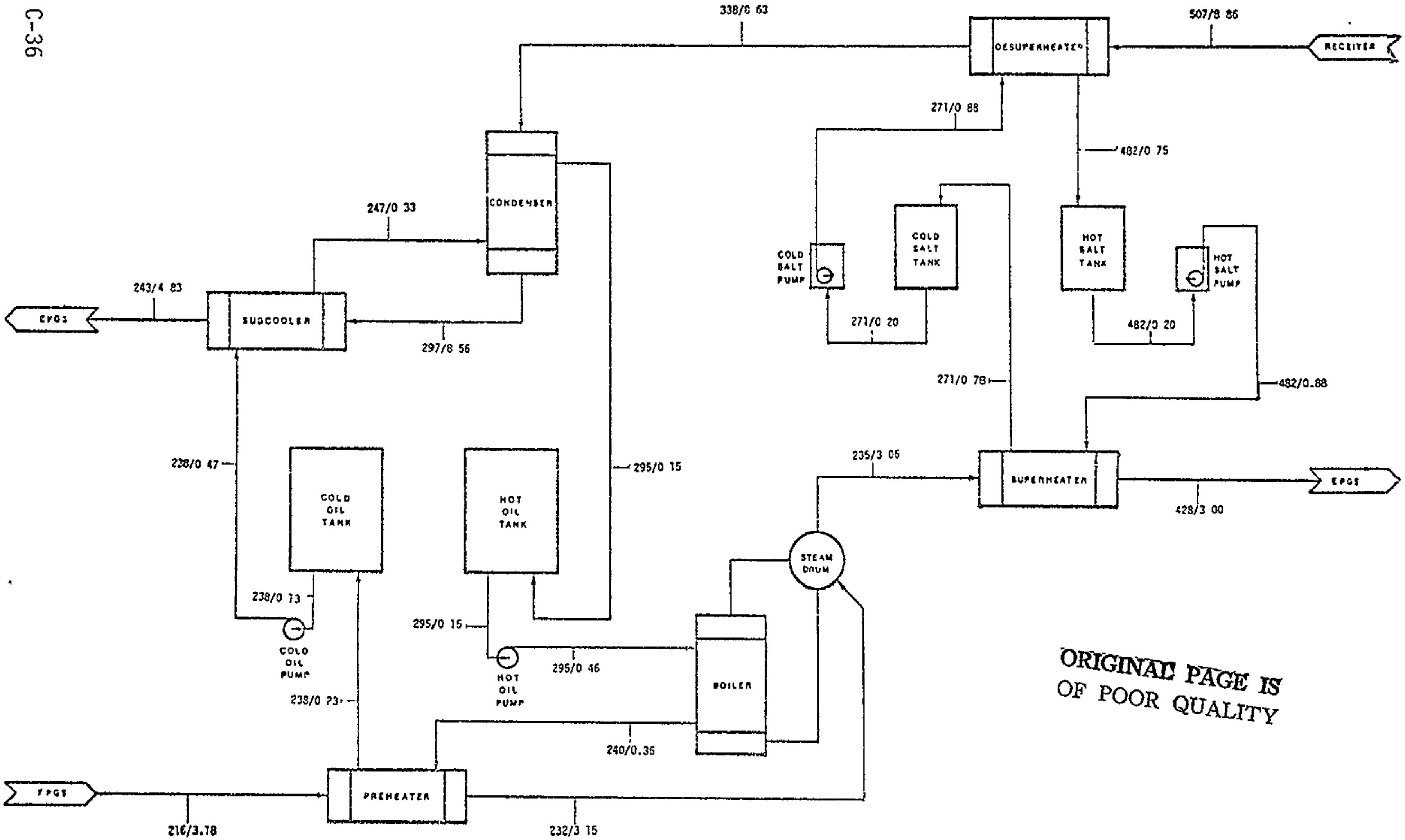
CHARACTERIZATION

Medium	211,311	Oil (Caloria HT43), 238-295°C and molten salt (HITEC), 271-482°C in separate stages
Containment	23,25	Low pressure tanks without packed beds, two-tank system for salt, multiple for oil
Source of Heat	26	Prime steam generated in concentrating solar receiver
Utilization	3.21	Steam generated in indirect heat exchanger admitted to intermediate pressure turbine

DESCRIPTION

The background discussion relating to Concept Definition 22 applies equally here. This concept differs, however, in two important regards: a two-stage thermal storage system of molten salts and oil is used (rather than a single-stage, oil system), and the oil is transferred between hot and cold tanks (rather than a packed bed tank with a thermocline). Since the mode of operation of this system is essentially like that previously described, the balance of this discussion is limited to the characteristics and operation of the storage subsystem.

A schematic diagram of the thermal storage subsystem is shown in the figure. Note that both the charging and heat recovery lines consist of three separate heat exchangers: a desuperheater, condenser, and subcooler in the charging line; a preheater, boiler, and superheater in recovery line. The high temperature storage medium (molten salt) serves the desuperheater and superheater; the lower temperature storage medium (oil), the other exchangers. In charging, the superheated steam generated in the receiver raises the temperature of the heat transfer salt from 271°C, as drawn from the cold salt tank, to 482°C for storage in the hot tank. The steam then enters the condenser where it is condensed by heat exchange with the colder oil.



Source: Reference 61, p A-15.

The oil leaving the condenser at 295°C is pumped to a hot oil storage tank, and the water leaving the condenser is subcooled to 243°C for return to the steam cycle feedwater system.

For steam generation in the discharge cycle, feedwater at 216°C and 3.2 MPa is drawn from the steam cycle, preheated, and converted to saturated steam at 235°C in the boiler by heat exchange with the hot oil. The steam is then superheated to 422°C and 3.0 MPa by heat exchange with the molten salt and passed to the turbine.

The specific design described in the reference for a 150 MWe solar plant employs seven spherical, insulated oil storage tanks 23.2 m in diameter and two spherical, insulated salt storage tanks 15.8 m in diameter. Only six oil tanks are required to contain the volume of oil required by the system; the seventh, empty, tank facilitates the transfer by receiving heated (or cooled) oil and avoiding creation of a thermocline as a result of returning this oil to a tank at a different temperature. The oil tanks are constructed of mild steel, and the spherical shape is chosen both to accommodate temperature and pressure stresses and to minimize heat loss from the tank. The salt system employs two spherical tanks, each large enough to contain the entire salt charge. The cold salt tank is of mild steel, and the hot tank of stainless steel for salt containment above 454°C.

1-27-78

CONCEPT DEFINITION — VARIANT #23.1

PROPONENT(S)

Martin-Marietta Corp. - Floyd Blake
Georgia Institute of Technology - S.H. Bomar

References

61

CHARACTERIZATION

Medium	311	Eutectic heat transfer salt (HITEC, Partherm 290), 238°C - 482°C
Containment	25	Three low pressure tanks without packed bed
Source of Heat	26	Concentrating solar receiver as superheated steam generator
Utilization	3.21	Steam generation in indirect heat exchanger

DESCRIPTION

Where Concept 23 involves a two-stage thermal storage system with oil as the first stage medium and molten salt as the second, this variant uses molten salt in both stages. Two configurations are possible: independent salt loops for the two stages, and dependent loops in which the "cold" tank of the high temperature stage functions also as the hot tank of the low temperature stage. An optimization study involving the two configurations and the salt storage temperatures indicates that the dependent system is preferable since it requires three tanks rather than four with the salt temperatures set at 238°C, 294°C, and 482°C. As in Concept 23, the temperature swing between the two lower values is associated with water preheating and evaporation on discharge and condensing and subcooling on charge, while that between the two upper values is associated with superheating on discharge and desuperheating on charge.

1-27-78

CONCEPT DEFINITION #24

PROPONENT(S)

Honeywell, Inc.

References

51

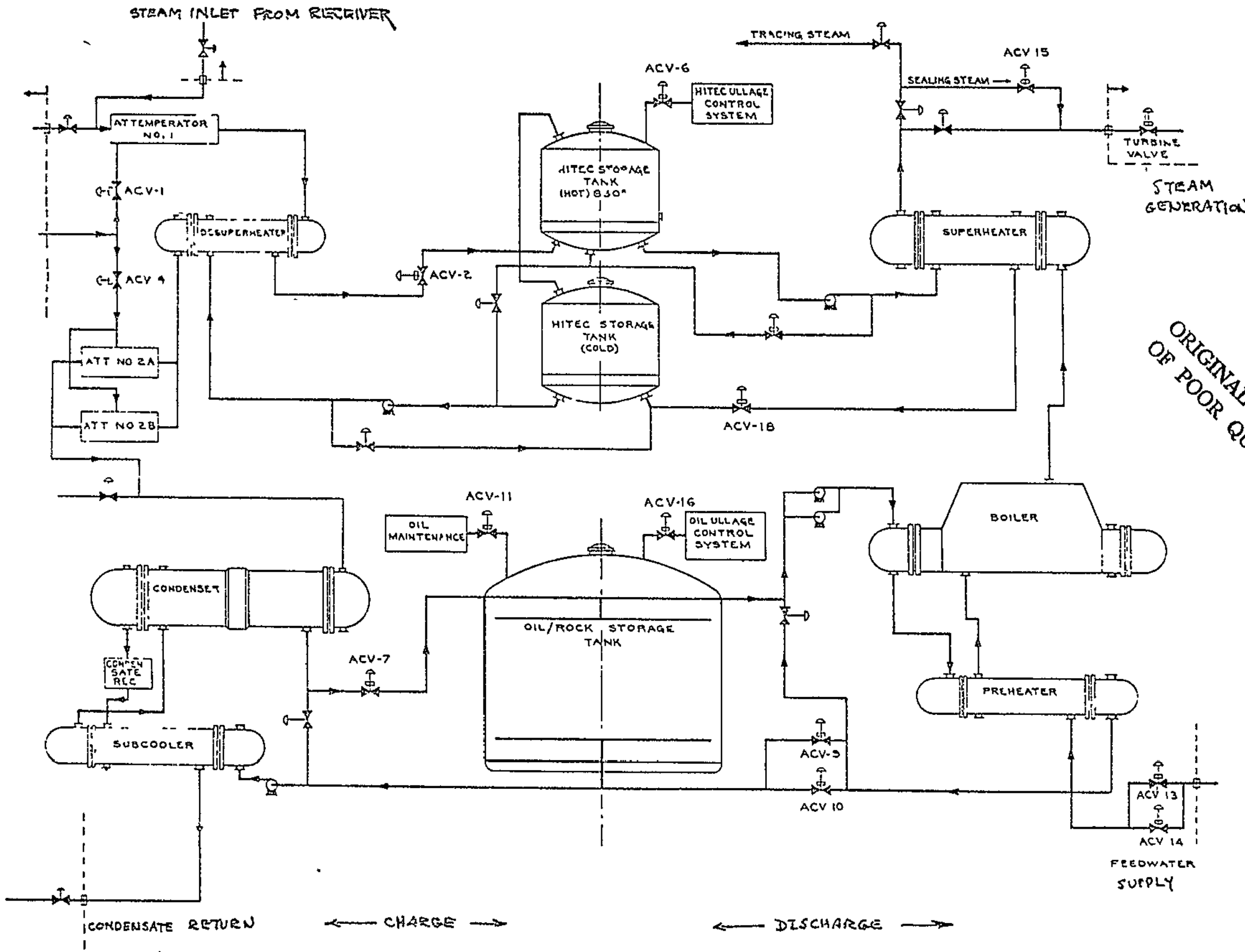
CHARACTERIZATION

Medium	211 and 52,311	Oil (Caloria HT43) and rock in first stage, 249°C - 303°C; molten salt (HITEC) in second stage, 299°C - 454°C
Containment	21,23	Low pressure, packed bed tank with thermocline in first stage; two tanks (hot and cold) without packed bed in second stage
Source of Heat	26	Prime steam from concentrating solar receiver
Utilization	3.21	Steam generation in indirect heat exchangers

DESCRIPTION

Like Concepts 22 and 23, this heat storage subsystem is part of a concentrating, solar-powered electric plant in which the turbine receives steam from the receiver subsystem and/or the thermal storage subsystem and supplies those subsystems with feedwater. This concept combines the oil-filled, packed rock bed, single tank with thermocline featured in Concept 22 with the use of molten salts for the superheating and desuperheating stages as described in Concept 23. The system schematic displays the main equipment units.

The HITEC salt is cycled between two cylindrical, stainless steel tanks with dished heads mounted with their axes vertical in an insulated, concrete-walled, underground vault. For a 100 MWe plant, the salt tanks are sized for 130 MWht storage with a temperature swing of 299°C to 454°C. This results in 12.2 m diameter by 9.8 m height tank designs. The oil and rock filled main storage requires two cylindrical, vertical axis, aboveground tanks of 34.8 m diameter and 14.6 m height capable of storing 831 MWht with a 249°C to 303°C temperature swing. The thermal storage system is charged by prime steam at 510°C and 10.10 MPa. On discharge, it generates steam at 391°C and 3.62 MPa at a maximum rate of 285.5 MWt for admission to the 70 MWe turbine generator. Feedwater is returned to the steam generator at 190.5°C.



(Source: Reference 51, Figure 3-21 - Thermal Storage Schematic)

1-27-78

CONCEPT DEFINITION #25

PROPONENT(S)

Bechtel Corp. - William Stevens

References

6

CHARACTERIZATION

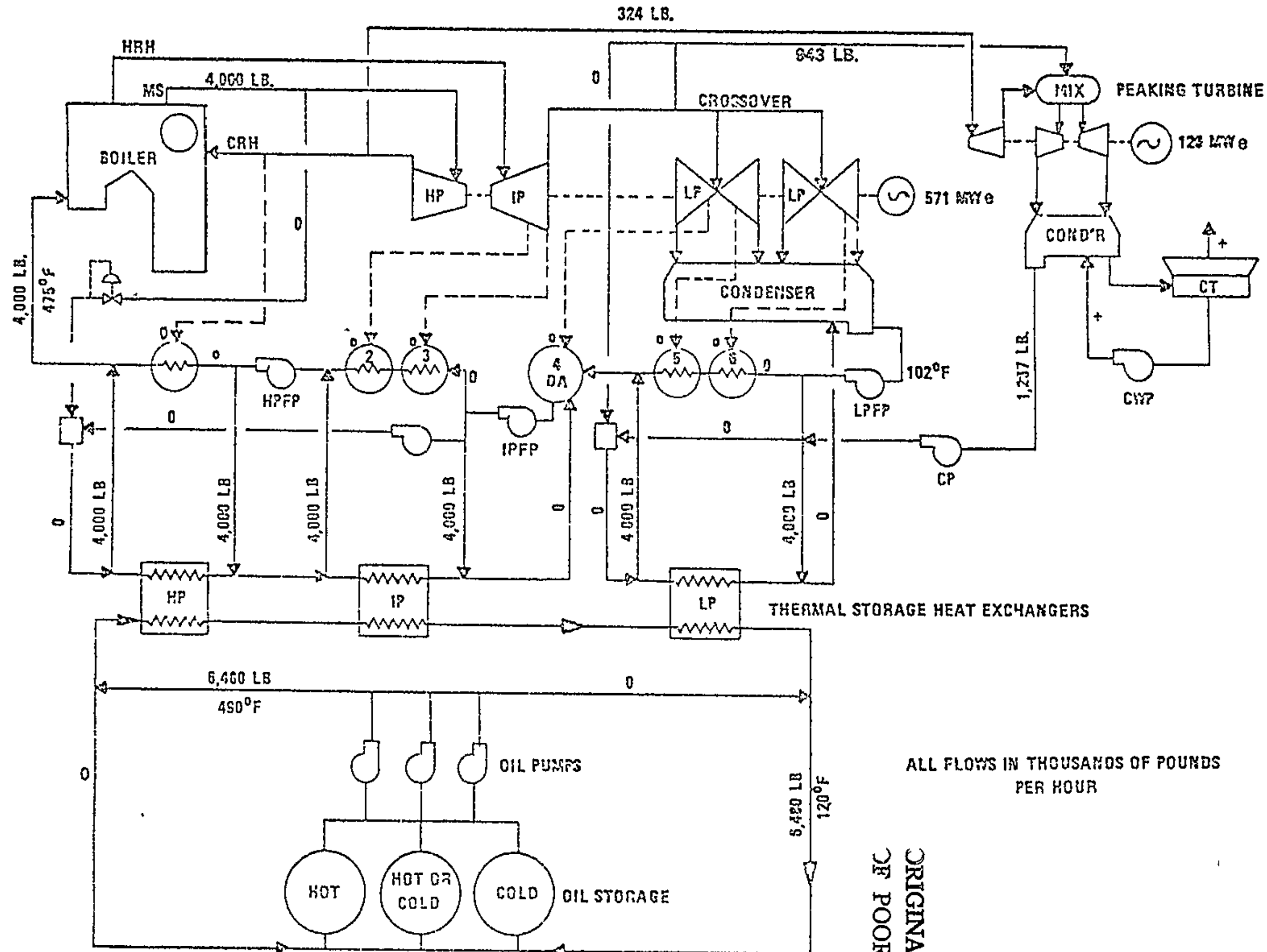
Medium	211	Oil (Caloria HT43), 38°C - 260°C
Containment	25	Multiple, atmospheric pressure tanks without packed bed
Source of Heat	23,26	Prime steam from high pressure and crossover lines
Utilization	1.11	Feedwater heating

DESCRIPTION

The concept described here was selected as the preferred *retrofit* thermal energy storage (RTES) system for existing coal-fired or nuclear utility plants in this 1976 study. The study also concluded, however, that the fundamental idea of RTES does not warrant further investigation due to its added equipment requirement, high capital cost, excessive downtime for installation, and the relatively small fuel savings expected. Nevertheless, the concept is included for completeness and because of its similarity to Concept 21.

The present scheme uses the sensible heat of hot oil for feedwater heating, thereby replacing the energy that would otherwise be removed by extraction steam; a 16-17 percent increase in on-peak output is anticipated. It is noted, however, that the low pressure stages of standard design turbines are incapable of passing the roughly 50 percent increase in turbine exhaust flow that results from not extracting steam for feedwater heating. Consequently, a separate peaking turbine-generator is required in this retrofit application.

The schematic shows the system components as envisioned for a fossil-fueled plant and the flows during on-peak operation. Note that steam for the peaking turbine is diverted from the cold reheat line (CRH) and the crossover point and that the feedwater reheat flow is through the thermal storage heat exchangers. During off-peak periods, a portion of the main steam supply (MS) and of the low pressure supply at the crossover is diverted to charge the thermal storage system while the balance is used in the main turbine operated normally with extraction steam feedwater heating; the peaking unit is idle.



ALL FLOWS IN THOUSANDS OF POUNDS PER HOUR

Both this concept and number 21 use the stored heat of a hot hydrocarbon oil for feedwater reheating but they differ in the following particulars.

1. To avoid tapping multiple extraction steam locations in a retrofit installation, this concept diverts steam from only two points: the main steam line and the crossover.
2. A single train of heat exchangers is used in this concept for off-peak oil heating and on-peak feedwater heating, rather than the separate trains of Concept 21.
3. With the three oil storage tank arrangements used here (one for hot oil, one for cold, and one for either), the total tankage volume need be only 1.5X that of the oil rather than 2X as in the two-tank arrangement of Concept 21.
4. Finally, since this is a retrofit concept, a peaking unit is specified rather than the *ab initio* design of a main turbine capable of no-extraction operation.

CONCEPT DEFINITION #26

PROPONENT(S)

General Atomic Co.
Oak Ridge National Laboratory

References

95,53; 37,110

CHARACTERIZATION

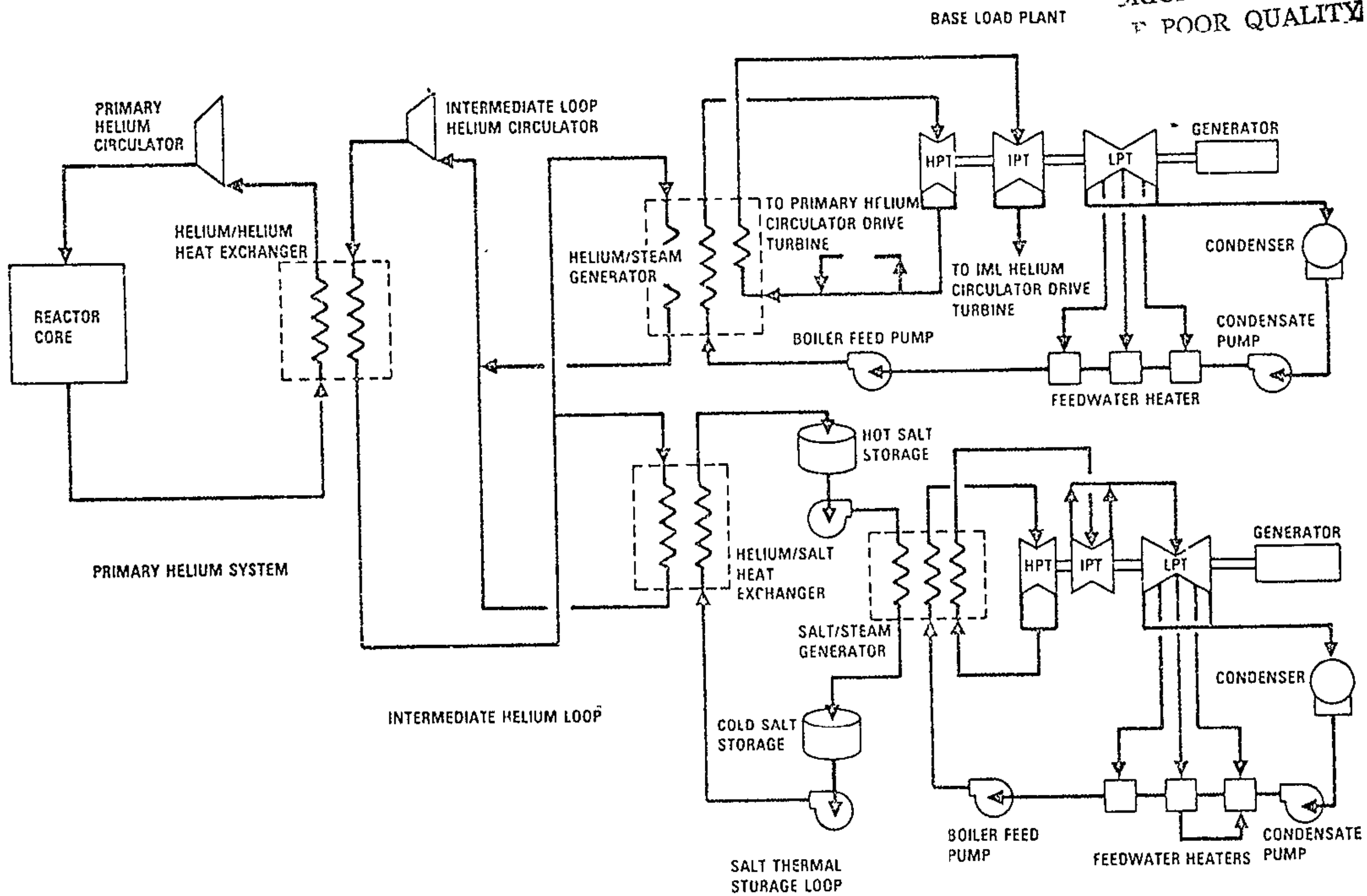
Medium	3111	Molten salts (HITEC), 288°C - 543°C
Containment	25	Multiple low pressure tanks without packed bed
Source of Heat	31	Intermediate helium loop of high temperature gas-cooled reactor
Utilization	3.4	Generate prime steam for peaking turbine

DESCRIPTION

This concept provides a means by which a high-temperature gas-cooled reactor operating at steady state can provide electrical power to a varying load by calling on thermal energy stored as the sensible heat of molten salt. The associated figure from Reference 95 illustrates the concept. Heat generated in the reactor core is transferred from the core-cooling primary helium loop to the intermediate helium loop which interfaces with the balance of the system. The intermediate loop flow supplies two heat exchangers in parallel. The first, a helium heated steam generator, powers a conventional steam cycle, base load plant. The second, a helium/molten salt heat exchanger, is used to charge the thermal storage system as the salt is transferred from the cold to the hot tank. To satisfy peak power demands, the hot salt is pumped through a steam generator to the cold storage tank, and the steam generated is used to drive a peaking plant turbine-generator.

The base load plant steam generator develops steam conditions comparable to those of modern fossil fueled plants: 510°C and 16.64 MPa at the high pressure turbine throttle and 538°C and 3.79 MPa in the hot reheat line to the intermediate pressure turbine. Feedwater is returned to the steam generator at 187°C and 20.44 MPa.

For the peaking plant cycle, the heat transfer salt at 543°C is cooled to 288°C as prime steam is generated at 483°C and 13.93 MPa


BASE LOAD PLANT
PRIMARY HELIUM CIRCULATOR
INTERMEDIATE LOOP HELIUM CIRCULATOR
GENERATOR
HPT
IPT
LPT
TO PRIMARY HELIUM CIRCULATOR DRIVE TURBINE
HELIUM/HELIUM HEAT EXCHANGER
HELIUM/STEAM GENERATOR
TO IML HELIUM CIRCULATOR DRIVE TURBINE
CONDENSER
REACTOR CORE
CONDENSATE PUMP
BOILER FEED PUMP
FEEDWATER HEATER
HOT SALT STORAGE
GENERATOR
HPT
IPT
LPT
HELIUM/SALT HEAT EXCHANGER
PRIMARY HELIUM SYSTEM
SALT/STEAM GENERATOR
CONDENSER
INTERMEDIATE HELIUM LOOP
COLD SALT STORAGE
BOILER FEED PUMP
FEEDWATER HEATERS
CONDENSATE PUMP
SALT THERMAL STORAGE LOOP
PEAKING PLANT

GA-A14160

and hot reheat steam 511°C and 3.86 MPa. Feedwater at 188°C and 15.79 MPa returns to the steam generator.

The salt storage tanks are free-standing conical-roofed, cylindrical vessels of conventional design. The cold tank is of carbon steel and the hot tank of stainless steel. Tank wall plates are tapered in thickness from bottom to top to match the reducing stress. Tanks are insulated on the exterior to reduce surface temperature to 66°C. In the application described, associated with a 2000 MWt reactor, four hot salt tanks and four cold salt tanks, each 36.6 m i.d. and 17.4 m high, are required. The ullage space in the system is filled with nitrogen at slightly above atmospheric pressure.

CONCEPT DEFINITION #27

PROPONENT(S)

General Electric Co.-Space Division

References

134, 38

CHARACTERIZATION

Medium	5,21	Fixed rock bed (type unspecified) plus a minimum quantity of oil as a heat transfer fluid
Containment	23	Multiple, low pressure tanks with packed bed; establish thermocline
Source of Heat		Unspecified, other than solar energy system
Utilization		Unspecified

DESCRIPTION

The essence of this concept is its use of gravity-fed trickle flow of oil as a heat transfer fluid through a rock bed as the heat storage medium to both charge and discharge the system. This form of sensible heat storage was proposed for use with various solar energy systems in which it could be adapted to particular temperature ranges by the appropriate choice of oil.

Heat transfer accomplished by a thin film of oil covering the rock is expected to be more effective than the usual convective mechanism occurring in a dual-medium, oil-filled rockbed. The higher heat transfer coefficient of the oil film also results in more rapid response of the storage medium, thereby maintaining a sharp thermocline as the oil temperature varies through the charge/discharge cycle.

The rockbed is contained in unpressurized, nitrogen-blanketed tankage of either of two designs. The first design consists of one small tank and two or more (as necessary for sizing) large tanks; the second, of one or more large tanks compartmentalized by insulated separators. Appropriate valve and pump arrangements permit charging/discharging the separate tanks or compartments in series or in parallel. The purpose of these configurations is to enable full high temperature response from a subvolume when the total system is only partially charged, since the charge and discharge flows are in the same direction. In either design, the rockbed rests on a support plate over the

oil sump and is topped by a perforated oil distribution plate; no complex manifolding is needed.

The small oil inventory, about 10 percent of the void volume plus that necessary to fill heat exchangers and piping, permits use of a more expensive oil without incurring a severe economic penalty. For applications to about 316°C, the more expensive Therminol-66 would be preferred to cheaper hydrocarbon oils because of its better stability and greater heat capacity.

CONCEPT DEFINITION #28

PROPONENT(S)

M. Riaz, et al - University of Minnesota

References

76-80, 10, 11, 48, 68, 70

CHARACTERIZATION

Medium	51,52	Rock bed (silica, granite, etc), 250°C - 500°C
Containment	53	Packed bed in unpressurized excavations
Source of Heat	33	Hot air from unspecified source as heat transfer fluid
Utilization	3.4,other	Steam generation by indirect heat exchange with hot air

DESCRIPTION

The referenced concept is not so much a particular system as a continuing investigation of the properties of large scale, underground or near-surface prepared rock beds as high temperature (250°C - 500°C) heat accumulators capable of storing energy for up to six months. Energy derived from off-peak excess thermal energy from power plants, may be stored in large-volume packed beds of native earth or rock materials, and recovered at rates appropriate for seasonal load leveling.

The basic accumulator configuration is an array of trenches filled with pebbles, crushed rock, or naturally formed porous rock and surrounded by undisturbed earth. Various arrangements of manifolds at the top, center, and bottom of the beds to direct the air flow are investigated. The basic mode of operation is to charge the bed by means of a hot air flow in one direction, and to recover the heat at a later time by a cold air flow in the opposite direction. Results indicate that there is a range of designs and construction methods offering the potential for stable heat storage with acceptably low flow work. The studies include an investigation of the thermal properties of native rock and methods of modeling the two-phase heat transfer between rock and air.

CONCEPT DEFINITION #30

PROPONENT(S)

Robert H. Turner - Jet Propulsion Laboratory

References

91

CHARACTERIZATION

Medium	41	Steel to 400°C
Containment	1	Storage media self-contained hollow steel ingots
Source of Heat	21,26	Steam
Conversion	-	

DESCRIPTION

This concept features a base load power plant integrated with a thermal storage unit. The thermal energy is stored in the form of heat in hollow steel ingots which come in direct contact with the working fluid (steam) of the power cycle. The source of energy for charging is from extracted steam. The storage vessel and the storage medium are one and the same in this concept. It consists of ingots of steel which have square cross section with a hole in the middle. These ingots are essentially thick square pipes stacked one on top of another. During off-peak hours steam is passed through a system of manifolds to hollow section of the ingots, thus storing heat in the steel. During peak hours water is fed through the manifolds to the steel ingots, thus exchanging heat from the steel to the water for the purpose of either feedwater heating, boiling, or superheating. No favored or optimum cycle arrangements or extraction points are mentioned.

1-25-78

CONCEPT DEFINITION — VARIANT 30.1

PROPONENT(S)

Robert H. Turner - Jet Propulsion Laboratory

References

91

CHARACTERIZATION

Medium	41	Steel to 400°C
Containment	11	Storage media self-contained, hollow steel sandwiches
Source of Heat	21,26	Steam
Conversion	-	

DESCRIPTION

This concept is identical to Concept Definition 30 in principle of operation. Its variation comes in the area of fabrication and leads to a significant reduction in cost. Rather than using hollow steel ingots, hollow electroslag welded steel sandwiches are used. These sandwiches are constructed by taking two steel plates, that are held apart by two narrow spacers which run the length of the sides of the plates, and electroslag welding the spacers and plates together. By using this method of fabrication the cost per pound can be reduced from 45¢ per pound for ingots to 30¢ per pound for the sandwiches. This is a cost reduction of 33 percent for the storage container/media.

CONCEPT DEFINITION — VARIANT 30.2

PROPONENT

Robert H. Turner - Jet Propulsion Laboratory

References

91

CHARACTERIZATION

Medium	41	Steel and sand to 400°C
Containment	11	Steel tube matrix
Source of Heat	21,26	Extracted steam
Conversion	-	

DESCRIPTION

In this variation sand is used as a solid storage media to replace some of the steel. This system consists of a matrix of steel tubes which are closely packed together. Around the tubes is poured an inexpensive solid. In this case sand is used. The principles of operation from this point on are essentially the same as in Concept Definition 30. Off-peak steam is passed by a manifold to the steel tubes. This transfers heat directly to the steel and indirectly to the sand. During peaking the process is reversed and heat is transferred from the sand and steel back to water being passed through the tubes for either feedwater heating, boiling, or superheating. The advantage of this system over the preceding two variants is that the space between the pipes which had essentially been filled with steel before would now be filled with inexpensive sand, thus reducing the cost for the storage media.

2-15-78

CONCEPT DEFINITION — VARIANT #30.3

PROPONENT(S)

Robert H. Turner, Henry I. Awaya - Jet Propulsion Laboratory

References

91, 180, 181

CHARACTERIZATION

Medium	41,13	Slab steel and HTW store energy
Containment	11	The slab steel is the container
Source of Heat	13	Water from steam drum in boiler
Utilization	1.11	Replaces FWH

DESCRIPTION

A more recent concept now being analyzed was described by R.H. Turner on February 9, 1978. Using the concept of thick steel slabs assembled by electroslag welding as a low cost containment and storage medium, this variant assembles long slabs, 15.2 cm (6") thick into square containers, for example 81.3 cm (32") O.D. and 50.8 cm (20") I.D.

The concept is that there would be an array of these square channels as shown in Figures A and C from Reference 181, connected in series (or series/parallel). Steam put in one end would heat the iron, be desuperheated, condensed, and subcooled. In addition to the storage of heat in the steel, the condensed water would be retained in the containers as additional thermal energy storage.

Claimed advantages are the low cost of steel slab, compared to rolled plate for tanks; low cost of electroslag welding as an assembly means, increased storage energy density (over Variants 30 to 30.2) by using HTW as well as the steel for storage, and safety compared to large steel tanks or PCIV in that catastrophic failure of one of the square containers is less hazardous than catastrophic failure of one large tank.

Figure B from Reference 181 indicates a mode of use as feedwater loop perturbation. The highest temperature water is obtained by penetrating the boiler island to extract saturated water from the steam drum. Excess steam extraction and preheat by the economizer is required. On discharge steam extraction for FWH is reduced or eliminated and HTW from storage is injected into the steam drum. The main turbines must be designed for safe operation at the increased steam flow during this period. A thermocline mode of operation of the thermal storage unit is assumed, ie a moving interface between hot and cold water during charge and discharge.

FIGURE A

FOUR SIDED STEEL SLAG THERMAL ENERGY STORAGE UNIT.

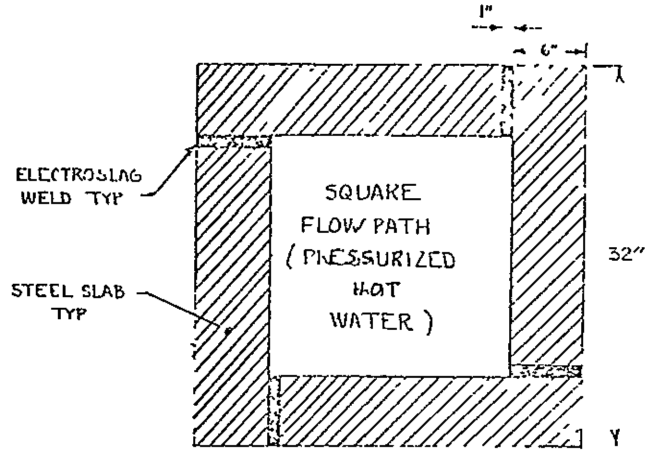


FIGURE B

THERMAL STORAGE UNIT FEEDWATER HEATING REPLACEMENT SCHEME

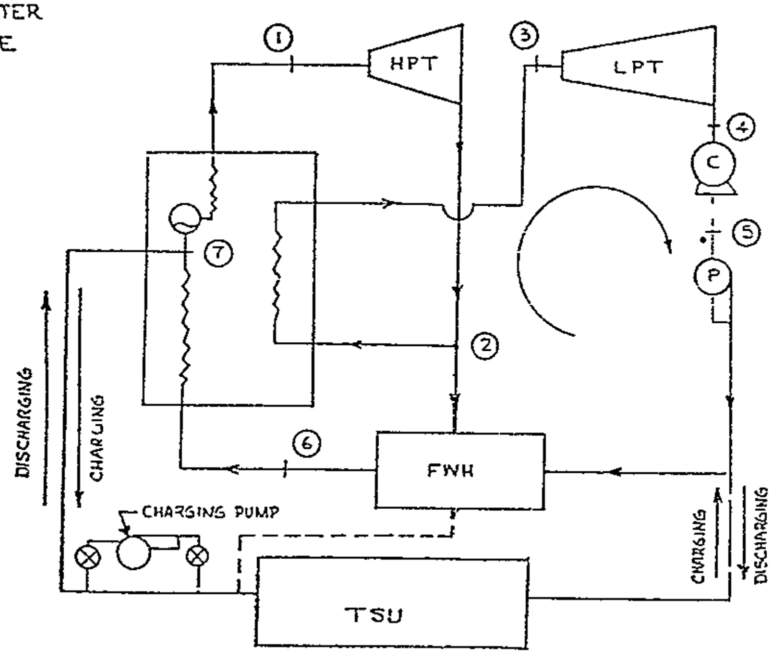
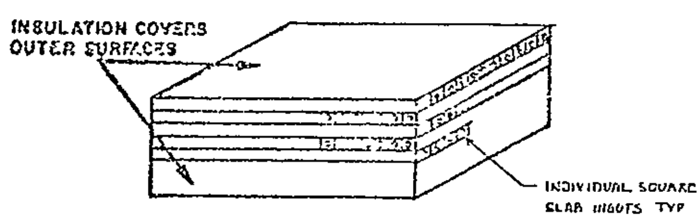


FIGURE C

OVERALL SQUARE SLAB THERMAL ENERGY STORAGE SYSTEM



CONCEPT DEFINITION #31

PROPONENT(S)

Energy Conversion Engineering Company - A. Selz

References

31, 105, 155, 171 (Sulfur data: References 27, 82, 87, 90)

CHARACTERIZATION

Medium	32	Molten sulfur, alone or with rock or iron packed bed
Containment	2	Low pressure tankage; number and arrangement unspecified
Source of Heat	1,2	High temperature water or steam from PWR
Utilization	3.21	Raise steam for peaking TG in indirect heat exchanger

DESCRIPTION

The essential feature of this concept is the use of liquid sulfur as a sensible heat storage medium. It is argued that low cost (<7.5 ¢/kg), presumptive long-term stability since it is an element, and liquid range (m.p. 115°C, b.p. 444°C) favor its use as a thermal storage medium.

The early references cited envision a liquid sulfur TES system employing a single, large, spherical tank of stainless steel (presumably operated with a thermocline) and used for load leveling by a nuclear PWR plant. Subsequent work has extended this concept to include dual-media systems of sulfur and fixed beds of rock or cast iron, the use of hydrogen sulfide at 3 atmospheres to reduce viscosity, the use of aluminized low-alloy steel for containment, and storage temperature swings of 85-100°C with the high temperature to about 430°C for fossil-fired generating plant applications.

It may be assumed that TES charging is accomplished by prime steam, and that utilization of stored energy is by steam generation to increase power; no specific power cycles are given.

CONCEPT DEFINITION #32

PROPONENT(S)

Boeing Engineering and Construction Co.

References

12, 13, 224

CHARACTERIZATION

Medium	62	Magnesium oxide firebrick checkerwork
Containment	11	High pressure, welded steel tankage operated with a thermocline
Source of Heat	31	Heated helium from concentrating solar receiver
Utilization		To heat helium for use in closed cycle gas turbine-generator

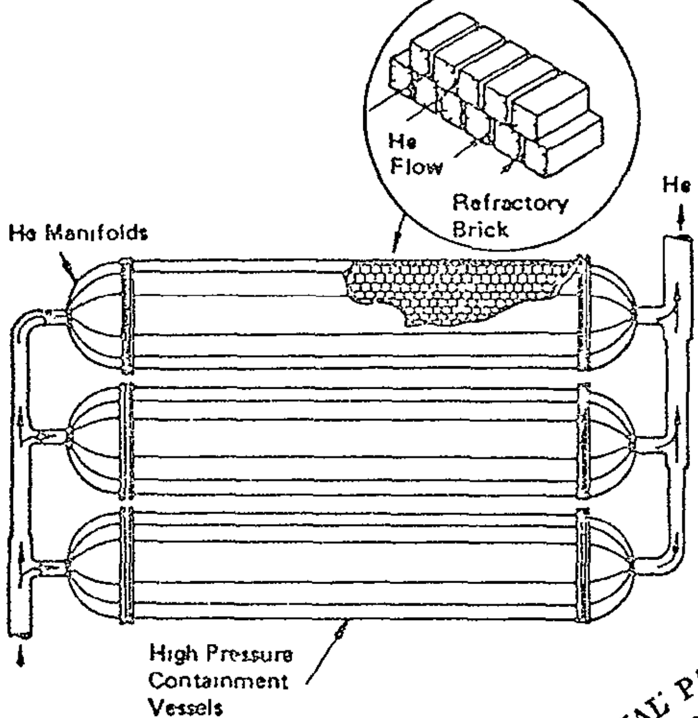
DESCRIPTION

This thermal storage concept is associated with a high temperature, helium-cooled, concentrating solar receiver and a closed-cycle, helium turbine, power plant. The storage unit consists of several parallel, high pressure, insulated, steel cylinders filled with a checkerwork of magnesia firebrick with manifolds at both ends (see illustration); the flow in each cylinder is distributed by a packed bed of alumina pebbles in the hemispherical endcaps.

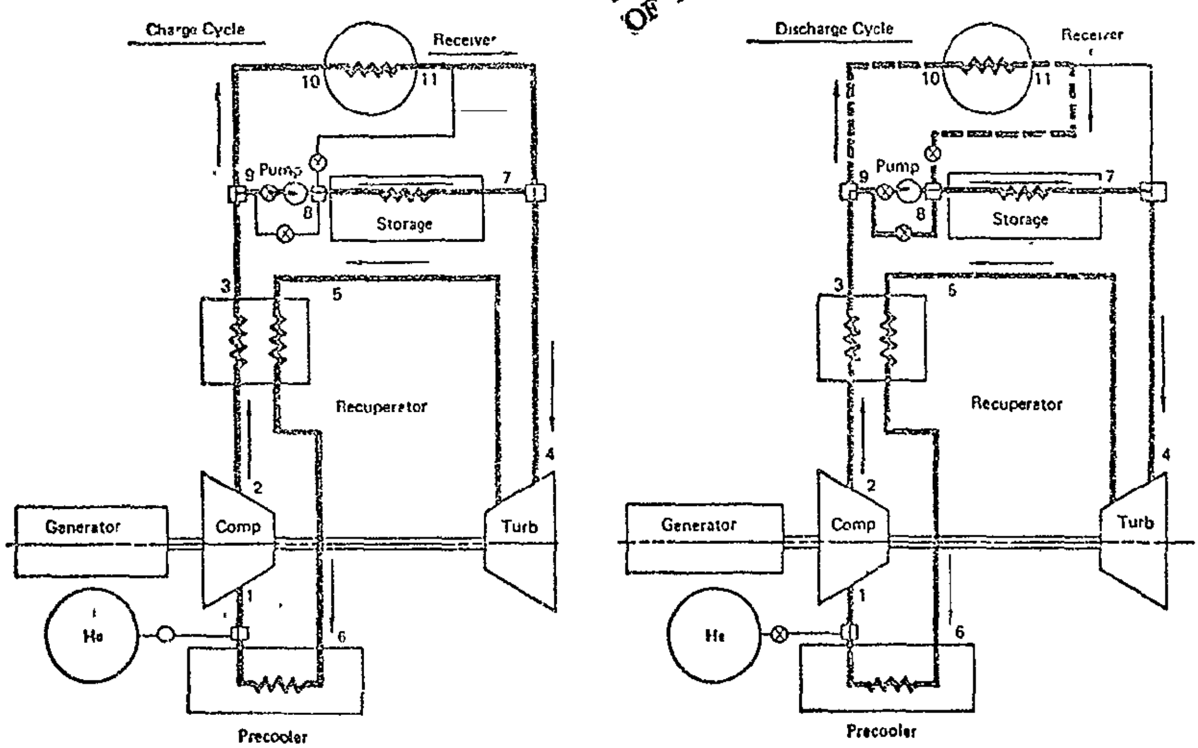
During the charge portion of a cycle, compressed helium is heated in the receiver and fed to the turbine and the storage unit in parallel. During discharge, the helium flow direction through the storage unit is reversed providing hot gas to the turbine as shown in the plant schematic figure.

Helium is delivered to the turbine at temperatures between 594°C and 816°C. The storage medium temperature swing is approximately 264°C. A turnaround efficiency of 72 percent is reported.

Cast iron bricks and magnesia bricks are compared in Reference 224, with the higher cost per kg of iron being cancelled by the lower cost of containment because of higher density; resulting cast iron TES is 5 percent less costly than magnesia TES.



- Magnesia (MgO) brick checkerwork
- Temperature swing = 264°C (443°F)
- Critical technical problems
  - Brick erosion
  - He stream contamination
  - Large insulated pressure vessels



CONCEPT DEFINITION #33

PROPONENT(S)

University of Houston - R.E. Collins
SubSurface, Inc. - K. Davis

References

169, 170

CHARACTERIZATION

Medium	21	Hot oil
Containment	5	Unlined salt-dome solution mined cavern
Source of Heat		Not specified except solar
Utilization		No details

DESCRIPTION

The proponents suggest that solution-cavity storage of hot fluids in salt deposits is an economic alternative to hard rock excavation. Many products are now stored and recovered from such caverns including natural gas, hydrogen and oxygen, butane and propane, and ethylene. Crude oil reserves are also being so stored, so hot oil storage may be practical without liners for materials compatibility or stress transfer. Multimillion barrel capacity caverns are current (>200,000 m^3). For the pressurized gases and liquids stored, security, safety, reliability appears well tested. No example of hot fluid storage is given so thermal stress affects are unknown.

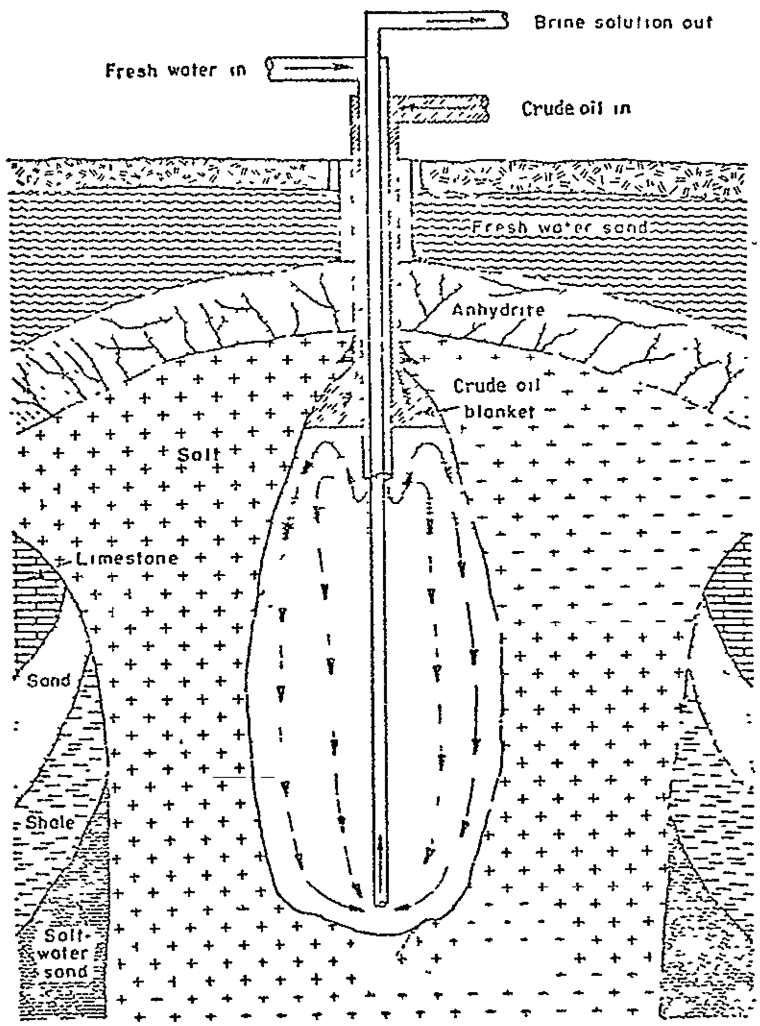
One of the proponents suggests solution mining with brine, replacing the brine with cold oil, and gradually raising the temperature by removing cool and injecting hot oil so stress transients are minimized. Separate hot oil and cold oil caverns are preferred with pressurized inert gas ullage forming a cap in each tank.

The possibility of packed bed (pebbles) is mentioned, to reduce oil costs, but this would appear to require a thermocline approach with risk of thermal stress.

Proponent estimates current cost of a two-cavern system (nearly half-a-million m^3 of excavation) at \$3.0 million, or 6.7 \$/m^3. Roughly 20 States have significant salt deposits as domes or beds.

Figure 2

SCHEMATIC OF A SALT CAVERN LEACHING OPERATION



7-21-78

CONCEPT DEFINITION #35

PROPONENT(S)

General Electric Co.-TEMPO — W. Hausz

References

Internal documentation — conceived during this project.

CHARACTERIZATION

Medium	5,21,31
Containment	22,23
Source of Heat	(See Concept Definitions 22, 24, and 27)
Utilization	(See Concept Definitions 22, 24, and 27)

DESCRIPTION

This concept is primarily a method of operating dual media, oil/rock or salt/rock storage systems with a smaller amount of heat transfer fluid (oil or salt) required yet retention of the conventional thermocline motion of Concepts 22 and 24 rather than the trickle charge method of Concept 27.

When large quantities of required storage make multiple modular storage tanks feasible, it is not necessary to have the voids filled with heat transfer fluid in all packed beds of rock, sand, and/or other minerals. Some fraction can be *drained beds* filled only with hot rock and an inert gas when fully charged; or filled only with cold rock and inert gas when fully discharged. Enough oil to fill the voids in at least three tanks, plus the pipelines and heat exchangers is adequate. For the sketch below, if N tanks are arrayed with say tanks 2 and 3 filled with cold oil and rock, tank 2 would be connected to the heat exchanger, cold oil pumped from the bottom of the tank, through the heat exchanger and back into the top as hot oil. When the thermocline in tank 2 has descended roughly three-fourths of the way to the bottom, tank 3 is connected to the heat exchanger to continue the charging operation. Meanwhile the oil in tank 2 is drained from the bottom, and pumped into the bottom of drained tank 4. The state of tank 2, lower quarter cold oil and rock, upper three-fourths hot oil and rock, is just such that all the oil will come out cold and the hot oil will heat the rock in the bottom quarter of the tank, providing that the relative heat storage in oil and rock are 1:3 (a function of the void volume). The process is continued, draining tank 3 to fill tank 5, etc until all are fully charged.

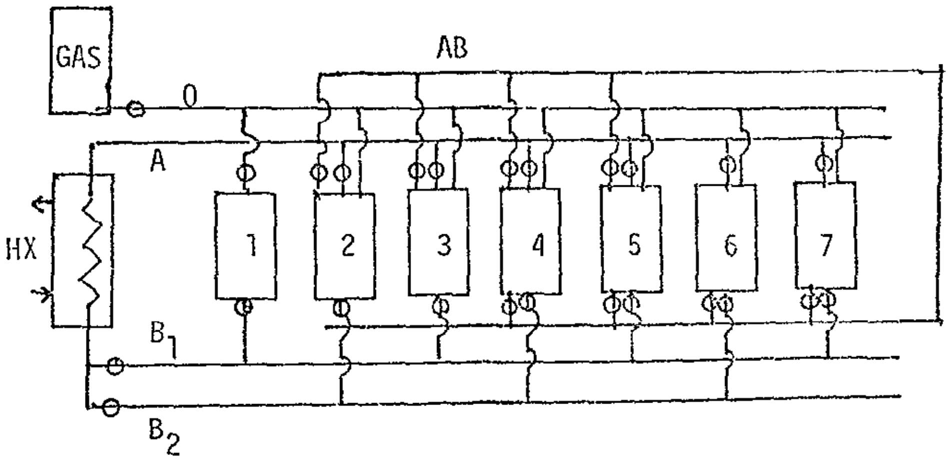


Figure 3. Tank and pipeline configuration.

In discharge a similar process pumps hot oil out of the top of a filled tank, say tank 2, through the heat exchanger, and pumps the resulting cold oil into the bottom of this tank until the thermocline is roughly three-fourths the way to the top. At this point the hot oil from tank 2 is switched to tank 4 to fill the void. The top of tank 3 is connected to the heat exchanger, a supplementary tank 1 delivers cold oil to the bottom of tank 3, and the cold end of the heat exchanger returns cold oil to tank 2. At the end of this step, tank 2 is full of cold oil, tank 3 is being discharged, and tank 4 is charged with both hot oil and rock. The process continues, with each tank being drained of its cold oil in the step described involving tank 1.

In addition to the continuing sequence transfers, a few extra steps are required at the end of the charge and discharge cycle to establish the desired conditions for the next cycle. The figure above indicates seven tanks, as many more as needed could be used, and five parallel transfer lines to connect top and bottom ends of the tanks to the heat exchanger and to each other in the cycle briefly described.

This concept has been expanded and described in a patent disclosure. The material in this report has been in part supported by DOE/NASA and in part supported by EPRI. The invention disclosure has been considered as a product of the research sponsored by EPRI, and assigned thereto.

CONCEPT DEFINITION #41

PROPONENT(S)

Xerox Electro-Optical System - J.A. Carlson

References

19

CHARACTERIZATION

None

DESCRIPTION

At this time a complete concept definition is impractical since the proponents have only submitted a brief project summary. However, their cycle representation is sensible and deserves attention.

Two different cycles are proposed using a PCM. One is a latent heat system, the other a hybrid latent-sensible heat system. The candidate fluids for both PCM and sensible were not discussed. Both systems were designed to be incorporated into a solar power plant.

System 1 (Figure 1) - Latent Heat Only

This scheme uses latent heat storage at two different temperature levels to produce a superheated vapor. Large temperature differences exist between

1. Collector temperature and lower storage level temperature.
2. Upper storage level and cycle temperature.

Large temperature differences mean more availability losses and this was the main reason for proposing a hybrid system.

System 2 (Figures 2 and 3) - Latent-Sensible

In this system, latent heat is used to preheat and boil a working fluid while sensible heat is used to superheat. Note that no large temperature differences exist between collector, storage, and cycle operating temperatures. Collection takes place at two different temperature levels for the latent and sensible points.

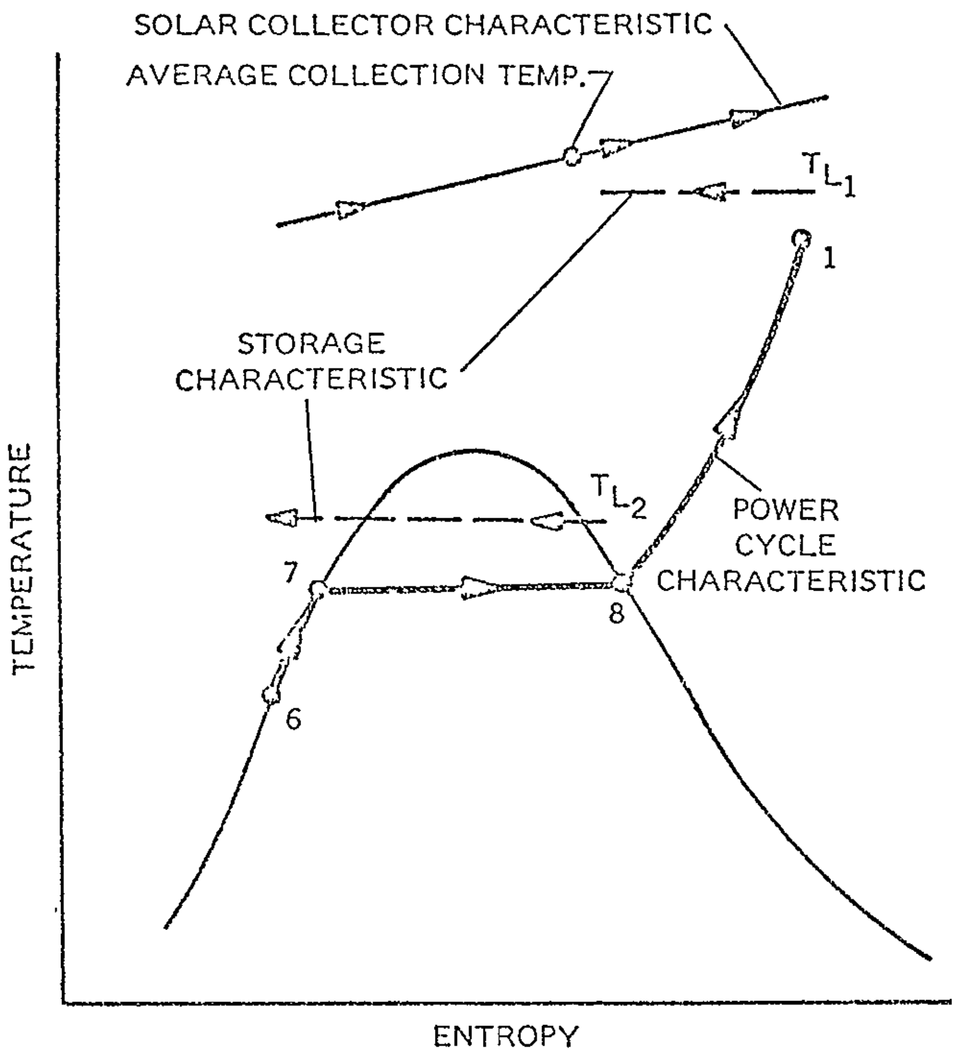

SOLAR COLLECTOR CHARACTERISTIC
AVERAGE COLLECTION TEMP.
T_{L_1}
1
STORAGE CHARACTERISTIC
T_{L_2}
POWER CYCLE CHARACTERISTIC
7
8
6
TEMPERATURE
ENTROPY

Figure 1.

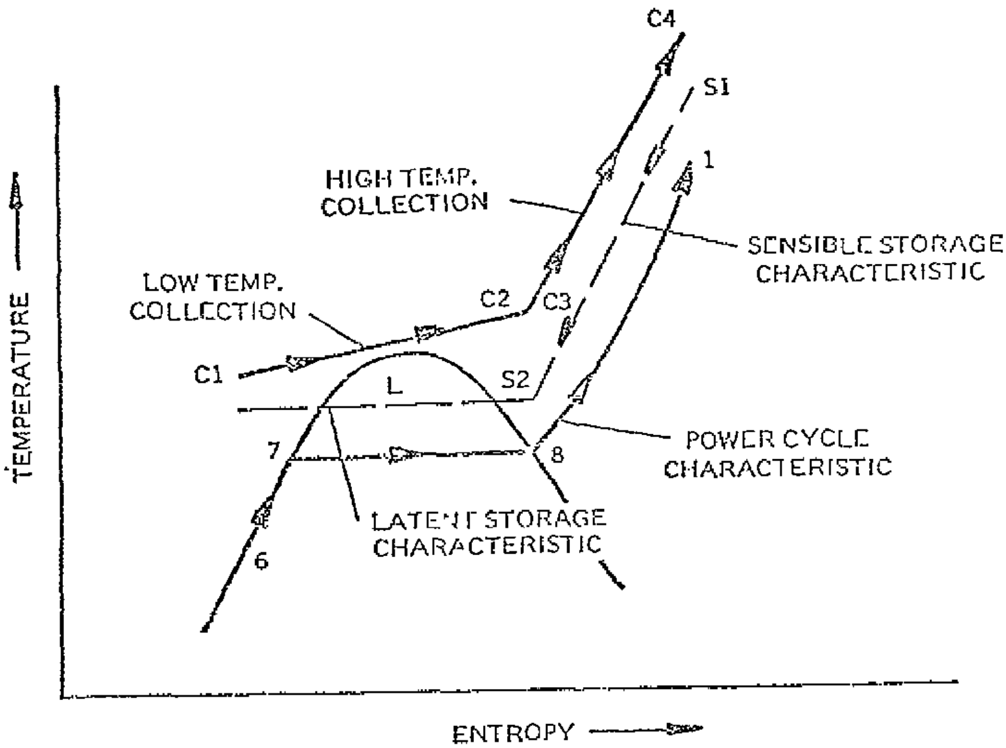


Figure 2

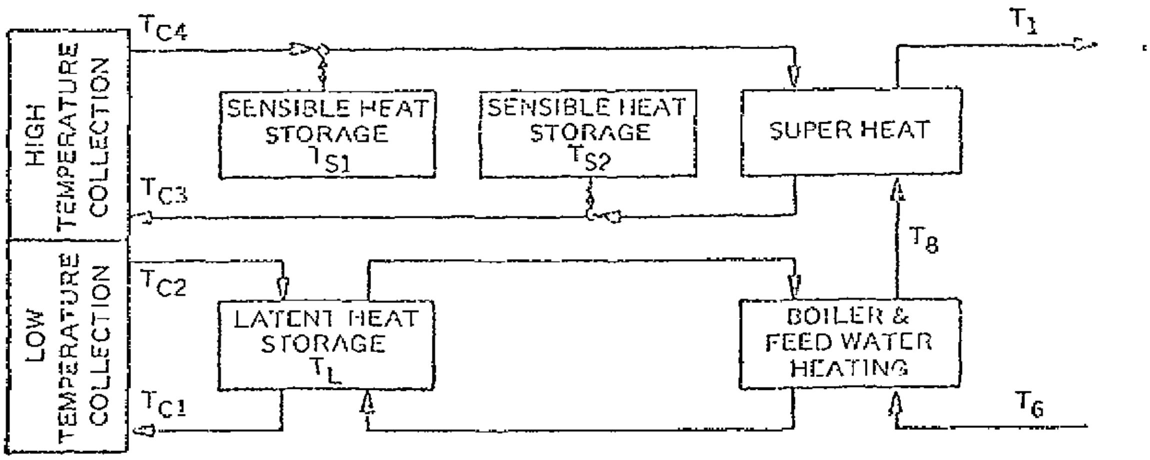


Figure 3.

Rev. 2-1-78

CONCEPT DEFINITION #42

PROPONENT(S)

T.A. Chubb - Naval Research Laboratory
J.J. Nemecek
D.E. Simmons

References

22, 102, 103, 104

CHARACTERIZATION

Medium	85	Molten salt ($MgCl$, $NaCl$, KCl; M.P. 385°C)
Containment	32	Low pressure tank, PCM encapsulated into packed bed
Source of Heat	37	Solar collector fluid, terphenyl
Utilization	4.22	Boiling and superheating steam in evaporating condensing heat exchanger

DESCRIPTION

This concept was developed for a solar thermal power plant, but is applicable to the present study because of its ability to follow a load curve.

The storage medium in this system is a PCM consisting of $NaCl$, KCl, $MgCl$.. This salt eutectic has a melting point of 385°C. The system consists of the salt sealed in cans hung in a rack inside of a pressure-tight tank. Each container has its entire surface area exposed for maximum heat tranfer area. In the bottom of the main tank is a system of heat release pipes which exchange heat from the solar collector fluid to a reservoir of heat transfer fluid, m-terphenyl (boiling point 365°C @ 1 atm). The heat causes the m-terphenyl to boil which in turn raises the pressure inside the main tank. The m-terphenyl then condenses on the cooler salt containers, releasing heat to the salt and causing it to melt. This continues until all the salt is melted after which point there is a rapid increase in temperature and pressure of the tank. The tank is said to be full once all the salt has been melted. In order to discharge the tank water is passed through a system of boiler/superheater pipes at the top of the tank. The m-terphenyl vapor condenses on these pipes, thereby exchanging heat with the water and causing it to boil and superheat

the steam. The condensing of the m-terphenyl lowers the pressure in the tank. At this lower pressure heat is tranferred from the salt to the m-terphenyl liquid causing it to evaporate off the salt container and thus replenish the condensing vapor. This process is continued until all the salt is frozen. During the time of evaporation the salt container is kept wet by a circulation system which sprays the liquid m-terphenyl over the salt containers.

The steam generated in the boiler superheater pipes is used to run a turbogenerator set. No mention of operating points of the turbine were made.

1-31-78

CONCEPT DEFINITION — VARIANT #42.1

PROPONENT(S)

T.A. Chubb - Naval Research Laboratory
J.J. Nemecek
D.E. Simmons

References

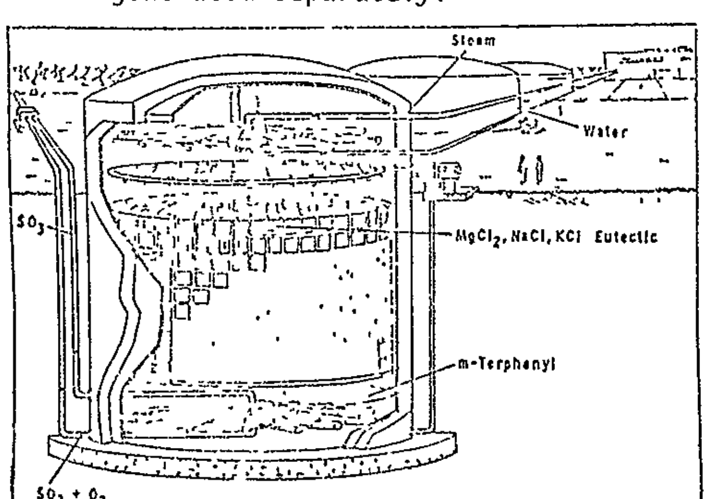
22, 102, 103, 104

CHARACTERIZATION

Medium	Molten salts 385°, 540°C
Containment	Low pressure tank Packed Bed PCM
Source of Heat	
Utilization	

DESCRIPTION

The proponents list a number of other salts and appropriate heat transfer fluids which may be used in the "Energy Storage-Boiler Tank" described in Concept Definition 42. The choice of the salt/heat transfer fluid pair depends on the temperature of storage desired. The proponents suggest that for large generation plants a two-temperature thermal storage system would be desirable. A possible choice salt and heat transfer fluid for a second temperature of storage, in addition to the one mentioned in Concept Definition 42, is CaCl, KCl, NaCl with a melting point of 540°C for the salt and P_2S_5 with a boiling point of 514°C for the heat transfer fluid. The proponents do not state what the exact usage of the two storage temperatures are, whether one temperature would be used for boiling and the other for superheating or whether steam of two temperatures and pressures would be generated separately.



2-2-78

CONCEPT DEFINITION #43

PROPONENT(S)

Comstock & Westcott, Inc. - B.M. Cohen

References

25

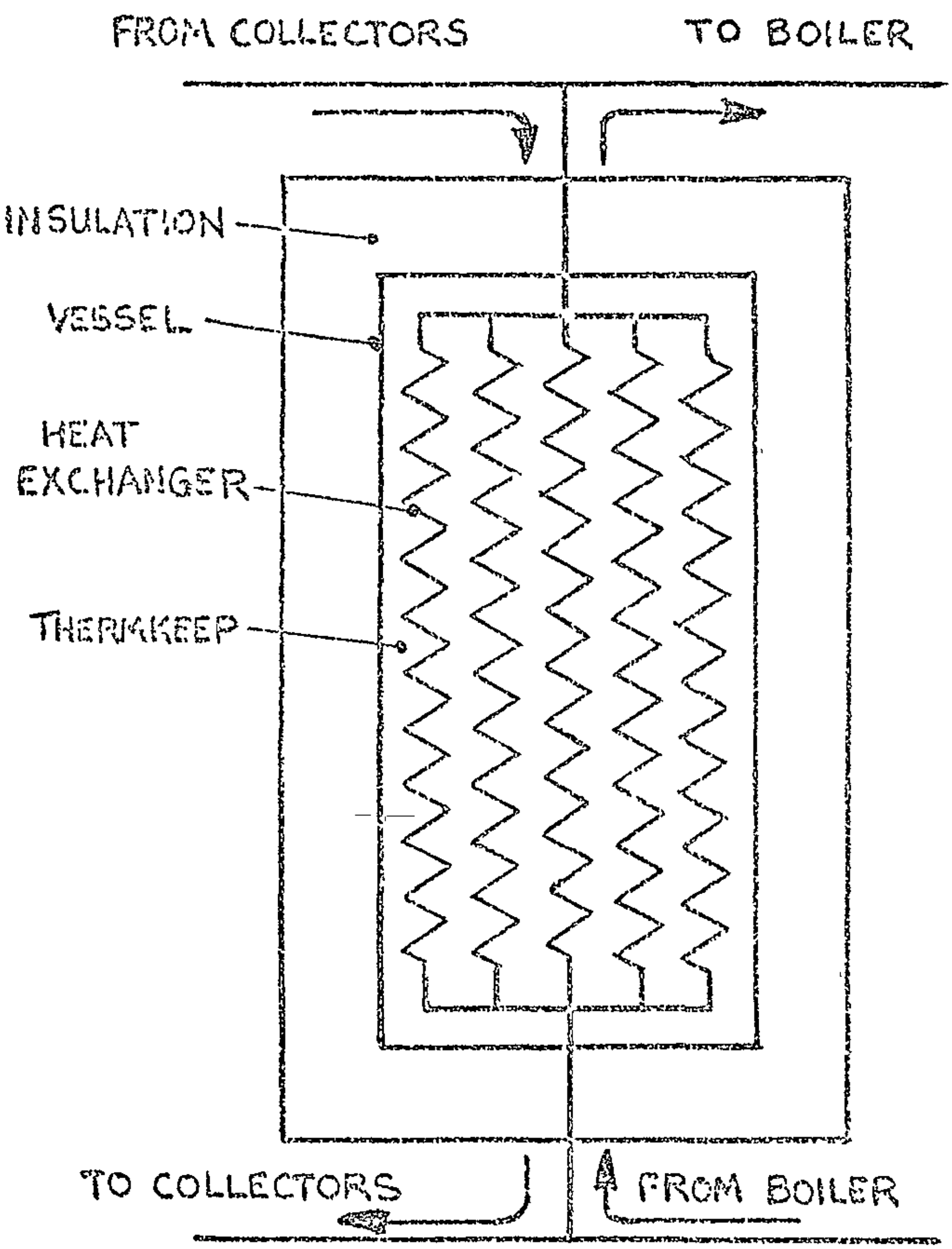
CHARACTERIZATION

Medium	81,84	Inorganic salt eutectic consisting of NaOH and $NaNO_3$
Containment	31	PCM in shell/HTF in tubes
Source of Heat		Solar
Utilization		Stored heat replaces heat from collectors during little or no insolation

DESCRIPTION

This system was designed for use in solar collecting systems, specifically for the Solar Total Energy Test Facility in New Mexico. At present no concrete design has been investigated because some computer modeling and conceptual remarks were made in their project summary.

The PCM selected is a salt mixture of 92 percent anhydrous NaOH and 8 percent $NaNO_3$ (known as Thermkeep) which undergoes a phase change between 240-310°C. The proposed working fluid is Therminol-66. The storage unit consists of an insulated vessel containing Thermkeep with a tubular heat exchanger immersed inside. T-66 enters at 310°C through the top and leaves at the bottom during charging It enters the bottom at 240°C during discharge. The top of the storage unit remains the hottest during both charge and discharge while, theoretically, no gradient should exist during steady-state. However, a recent personal communication with Mr. Cohen revealed that a slight gradient did exist in their small experimental unit currently being tested.


FROM COLLECTORS
TO BOILER
INSULATION
VESSEL
HEAT EXCHANGER
THERMKEEP
TO COLLECTORS
FROM BOILER

CONCEPT DEFINITIION #45

PROPONENT(S)

D.D. Edie, et al - Clemson University

References

32

CHARACTERIZATION

None

DESCRIPTION

The proponents discuss the possibility of a direct contact heat exchanger/storage system applicable to heat of fusion TES units. At the time of the project summary paper, September 1977, the selection of both a suitable PCM and immiscible fluid were underway with the latter proving to be more difficult. The proponent was concerned with temperatures lower than are of interest to us.

The system operates as follows: during charging the immiscible fluid (with a lower density than the PCM) enters the bottom of the storage tanks and travels upward, heating the PCM. During discharge the low temperature immiscible fluid (still being a lower density) is again injected into the bottom and is heated up by the salt. This is shown schematically in Figure 1.

Regarding the PCM selection, the proponents feel any number of inorganic salt hydrates would be suitable once criteria such as low cost, corrosiveness, heat of fusion, and temperature range were used to screen down to an appropriate number. For an initial study, they chose $Na_2HPO_4 \cdot 12H_2O$ as a suitable PCM (temperature range of 16 to 60°C).

The selection of appropriate immiscible fluids has provided only one "ideal" fluid, this being Exxon's Varsol 18. Several other fluids were investigated and tested (Dow Corning and several parafin hydrocarbons) but were rejected because of an emulsion which formed. This emulsion is viscosity dependent, however, and applications at higher temperatures would allow such fluids to be considered.

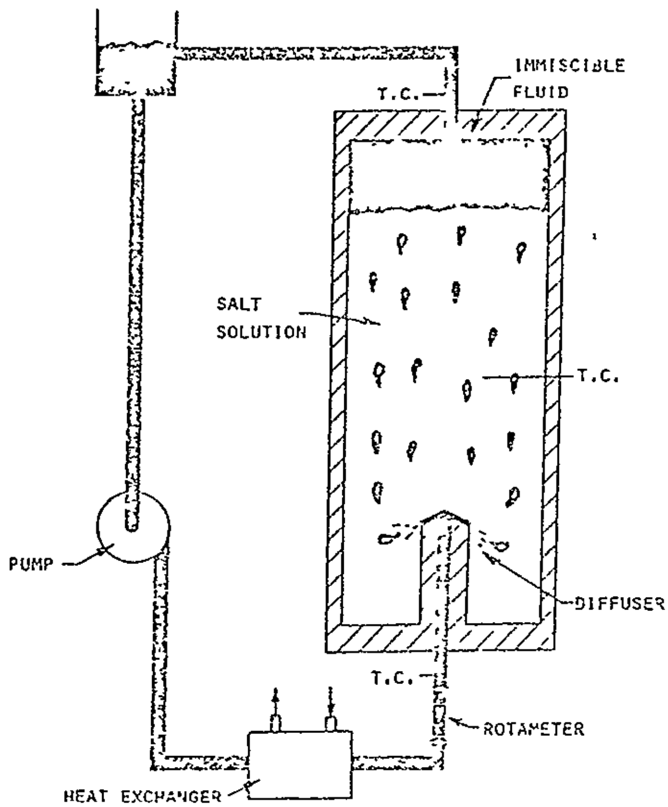


Figure 1. Immiscible fluid-heat of fusion storage system.

Varsol

Based on experimental data with the $Na_2HPO_4 \cdot 12H_2O$ and Varsol 18, storage efficiencies are three times greater than a water storage system operating at the same temperature range. It does seem inappropriate to make this comparison since water systems operating at higher temperatures have excellent storage efficiency and this concept has yet to be attempted at temperatures applicable to power plant operations.

CONCEPT DEFINITION #46

PROPONENT(S)

Honeywell Corp. - R.T. LeFrois

References

176

CHARACTERIZATION

Medium	81	Sodium nitrate + 1 percent NaOH
Containment	21	Steel tank
Source of Heat	.26	Solar application
Utilization	1,3.51	Liquid-solid PCM indirect HX in storage tank

DESCRIPTION

This concept is basically a PCM storage tank with condenser and boiler tubes for charging with live steam and discharging by vaporizing feedwater. The tank is square, built of thin (1.27 cm) plate walls stiffened by horizontal I-beams welded to the plate. The condenser is composed of horizontal tubes near the bottom of the tanks. The lower density of the melt causes convection adequate for agitation. The vaporizer tubes are also horizontal and near the top.

One novel feature is the use of an off-eutectic mixture of $NaNO_3$ plus 1 percent of NaOH. This is used over a narrow temperature band of temperatures, 298-303°C, which is well above the solid as line at 246°C and below the 300°C melt point of $NaNO_3$. A slush exists over the working temperature range. The tendency of a thick deposit of salt to reduce heat transfer at the vaporizer is inhibited by a novel scraper on each tube comprising a series of inclined plates with semi-elliptical holes that closely fit the circular tubes (as in the figure). A set of these plates is welded to a support rod. Two such support rods make the plates surround the tube. Two halves of a chain-drive sprocket hold the plates to a 0.13 mm tolerance around the tube. A chain drive rotates the rotary scrapers on a number of tubes, at up to 200 rpm.

A system based on this PCM concept was compared with the sensible heat concepts described in Concept Definition 24, (and in Reference 51). It appeared economically superior but had more technical risk. Some work has continued at Honeywell.

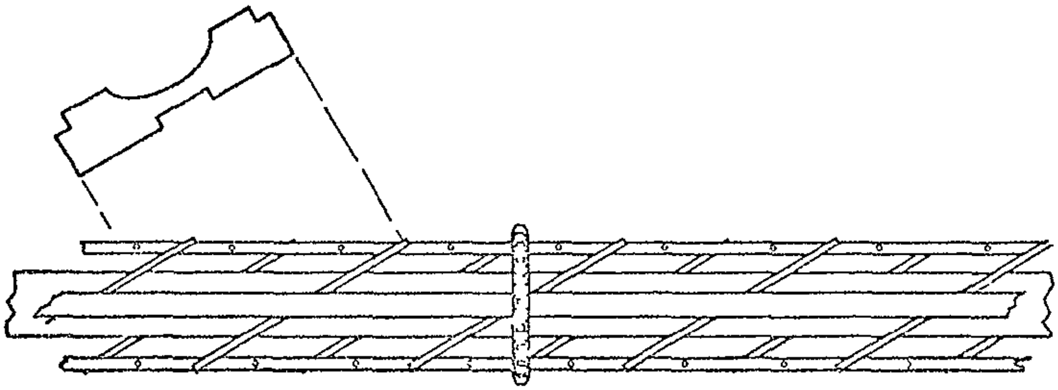


Figure 3-6. Split Design Inclined Plate Rotary Scraper

CONCEPT DEFINITION #47

PROPONENT(S)

J.R. Gintz - Boeing Engrg. & Construction

References

12, 13

CHARACTERIZATION

Medium	83	Inorganic eutectic salt consisting of $NaF-ZnF_2$
Containment	31	Buried concrete vessel
Source of Heat	31	Helium used in Brayton cycle of a solar energy power plant
Utilization		Heat stored can take place of receiver to heat helium

DESCRIPTION

The proposed concept was designed to be integrated into a solar power plant utilizing the Brayton cycle to smooth out fluctuations resulting from little or no insolation. This system stores energy for six hours, then discharges for six hours, producing 50 MW_e of power.

During times of direct sunlight, excess helium is sent through a modified tube/shell heat exchanger and liquefies the salt eutectic. The reverse procedure is initiated during discharge with the helium being used either to supplement or completely replace the heat source of the receiver.

The phase change storage concept is a buried square tank. The outer wall is constructed of reinforced concrete while refractory brick will provide the required insulation. The inside of the tank is to be lined with Hastalloy-N to avoid contact between insulation and salt mixture. The tubes ($\sim$30,000) are to be constructed of Inconel 617.

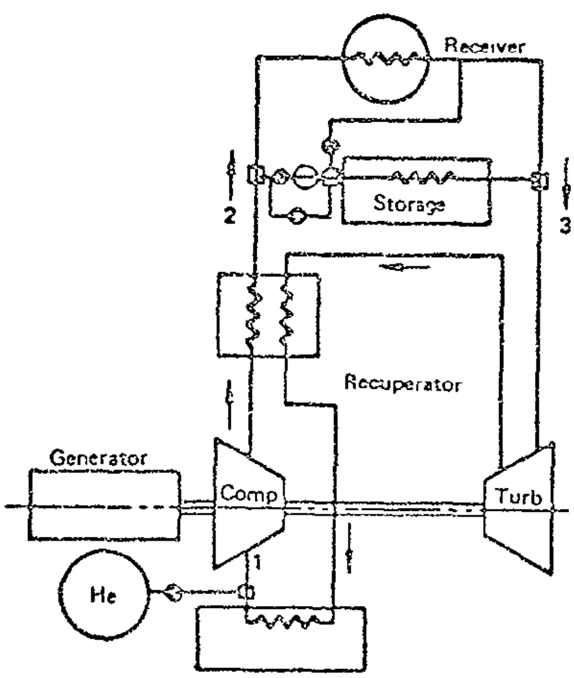
Salt Characteristics

T_{melt} = 640°C
ΔH_f = 143 cal/gr = 586 kJ/kg
Cost = 0.97 $/kg

Cost Analysis

Account	Quantity	Unit cost	Total cost (M $)
Salt (fluoride eutectic)	4 2 x 10^6 kg	0 97 $/kg	3 9
Storage container (square, 12 3 m x 12 3 m x 12 1 m)	722 m^3	970 $/$m^3$	0 7
Insulation	135 m^3	741 $/$m^3$	0 1
Heat exchanger (0.96 cm O D x 12 1 m) tubes	33,600 tubes	51 8 $/tube	1 7
welds	33,600 welds	12.0 $/weld	0 4
Manifold allowance (20%)			0 5
Helium circulation system	24 38 MW (pumping capacity)	53,500 $/MW	1 3
Total			8 6

This system has a turnaround efficiency of 62 percent.



State Point	Temp (°C)	Press (MN/m^2)
1	49	1.80
2	581	3.45
3	816	3.32

Figure 1-6. Storage Plant Schematic

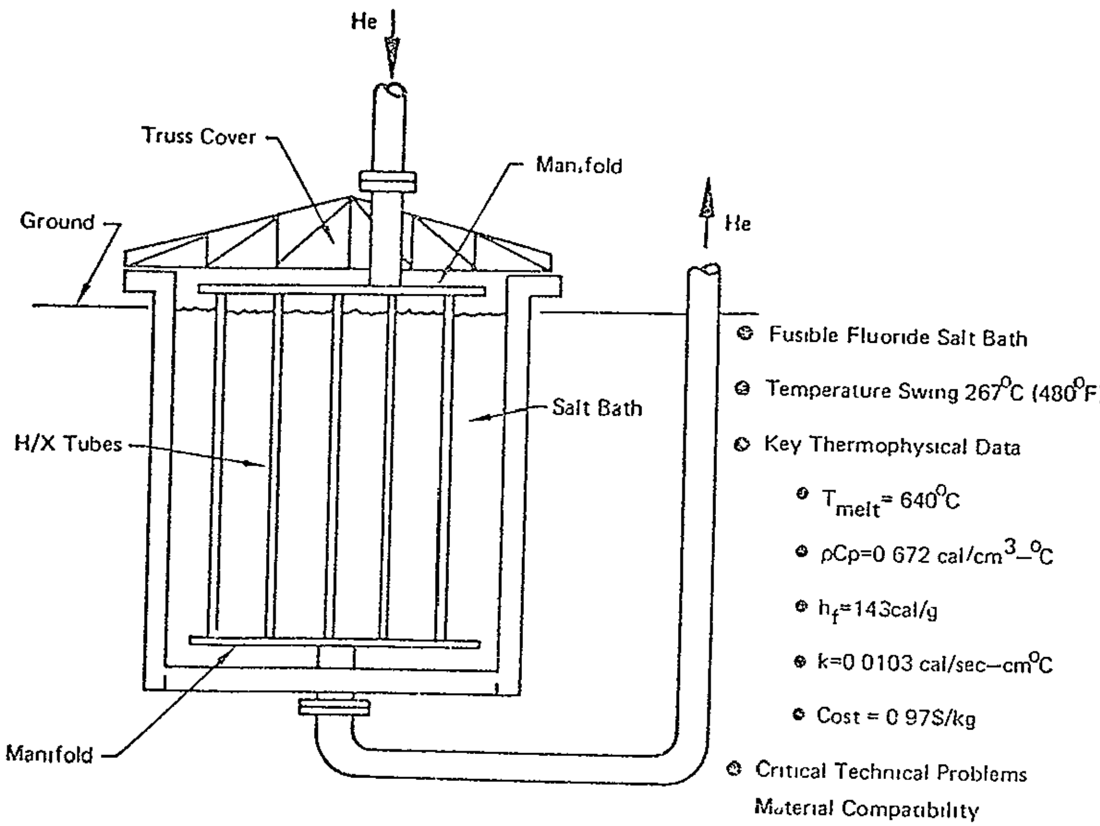


Figure 1-4. Phase Change Storage Concept

CONCEPT DEFINITION #48

PROPONENT(S)

Grumman Aerospace Corp. - Angelo Ferrara, George Yenetchi, Robert Haslett, Robert Kosson

References

35, 36, 132

CHARACTERIZATION

Medium	81,85	Inorganic PCM eutectics of either nitrates/nitrites or chlorides
Containment	31,33	Either tube/shell or liquid metal immiscible
Source of Heat	26	Prime steam (input to HP turbine)
Utilization	1.312	Heat either replaces FWH or steam generated for HP turbine

DESCRIPTION

This is one of several TES units proposed by Grumman as applicable to a supercritical fossil fuel plant with the following characteristics:

MW_{net} - 540
Throttle pressure - 24 MPa
Throttle temperature - 538°C
Reheat temperature - 538°C

The TES unit was designed to supply 5 percent of the peak power. The unit was two-stage and can be categorized as follows:

- Step 1: Single loop regenerative heating with the heat source obtained from main steam and used as a replacement in feed-water heating.
- Step 2: Single loop separate power conversion loop also receiving heat from the main steam but using heat in own power cycle for auxiliary power output.

Both TES units utilized the heat of fusion of a eutectic salt. However, analysis showed that sensible heat contributed to 30 percent of the total energy stored. For stage 1 two eutectics were used:

1 - $KCl \cdot NaCl \cdot MgCl_2$ storing 33 percent
2 - $NaCl \cdot NaNO_3$ storing 67 percent

For stage 2:

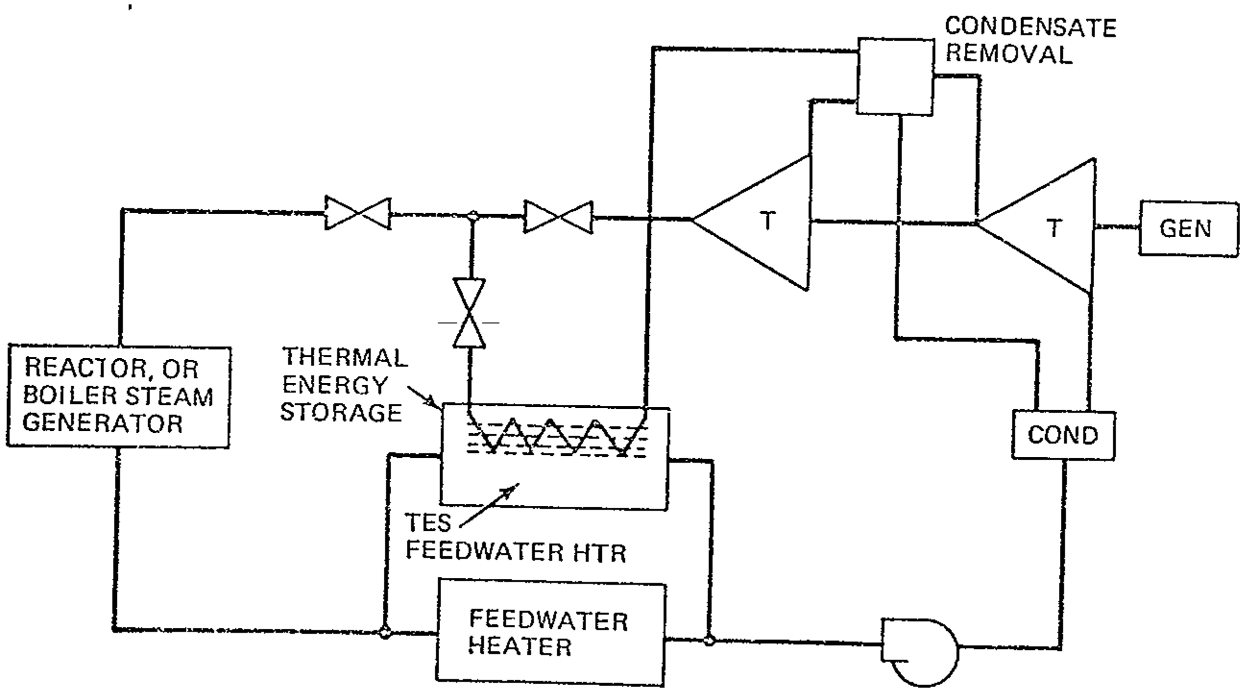
1 - $CaCl_2 \cdot KCl \cdot NaCl$	storing 16 percent	Vertically separated, counterflow HX
2 - $KCl \cdot NaCl \cdot MgCl_2$	storing 32 percent	
3 - $NaCl \cdot NaNO_3$	storing 52 percent	

The unit was designed to store energy over an 18-hour period and supply over a 6-hour period completing its daily cycle.

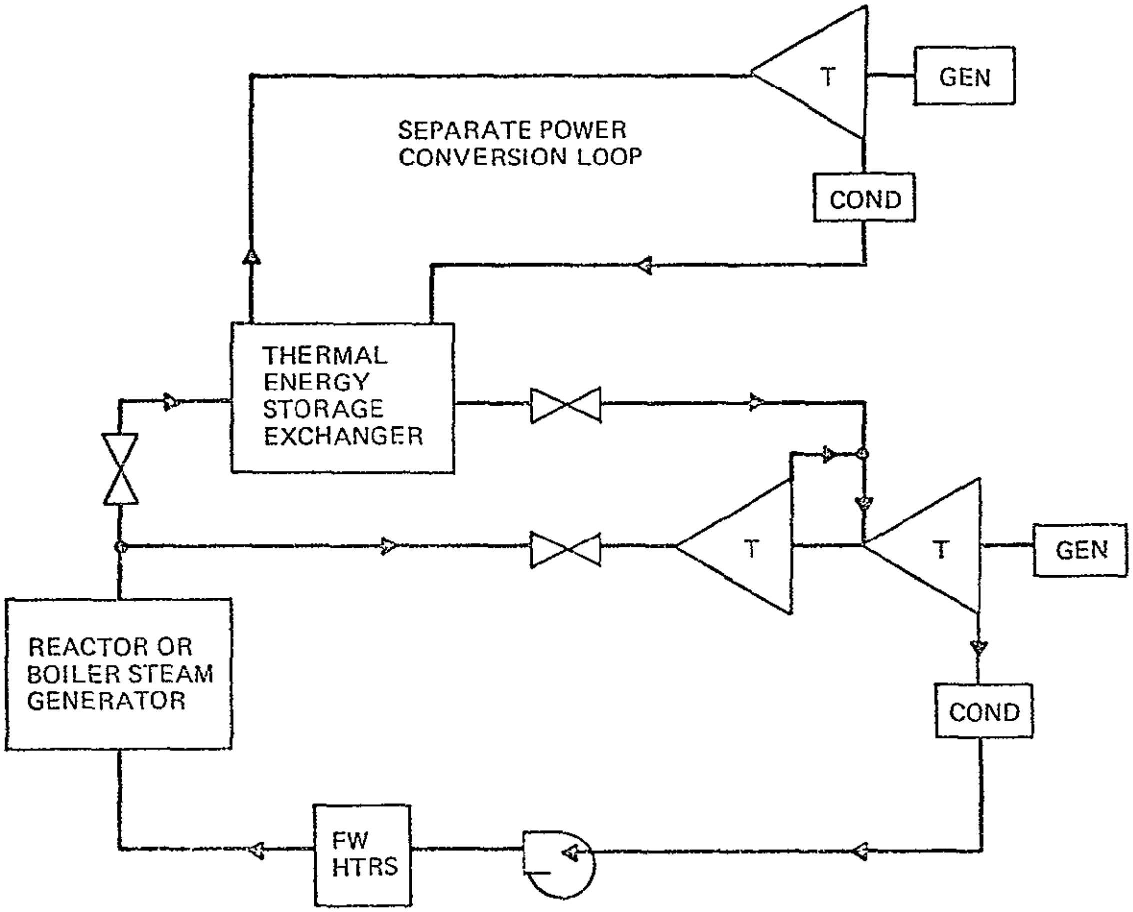
Two heat exchanger concepts were proposed. One was a tube/shell with the salt on the shell side while the other employed direct contact between salt and liquid metal with a separate liquid-metal/working fluid heat exchanger.

$$\frac{\text{Net Plant Heat Rate out}}{\text{Net Plant Heat Rate in}} = 0.97 \quad \text{(claimed ?)}$$

LOCATION 2 SINGLE LOOP REGENERATIVE HEATING AUGMENTATION



LOCATION 8 SINGLE LOOP SEPARATE POWER CONVERSION LOOP



CONCEPT DEFINITION — VARIANT #48.1

PROPONENT(S)

Grumman Aerospace Corp. - A. Ferrara, G. Yenetchi, R. Haslett, R. Kosson

References

132

CHARACTERIZATION

Medium	8	PCM eutectics, eg KCl · NaCl · $MgCl_2$
Containment	32	Thin walled macro-encapsulation

DESCRIPTION

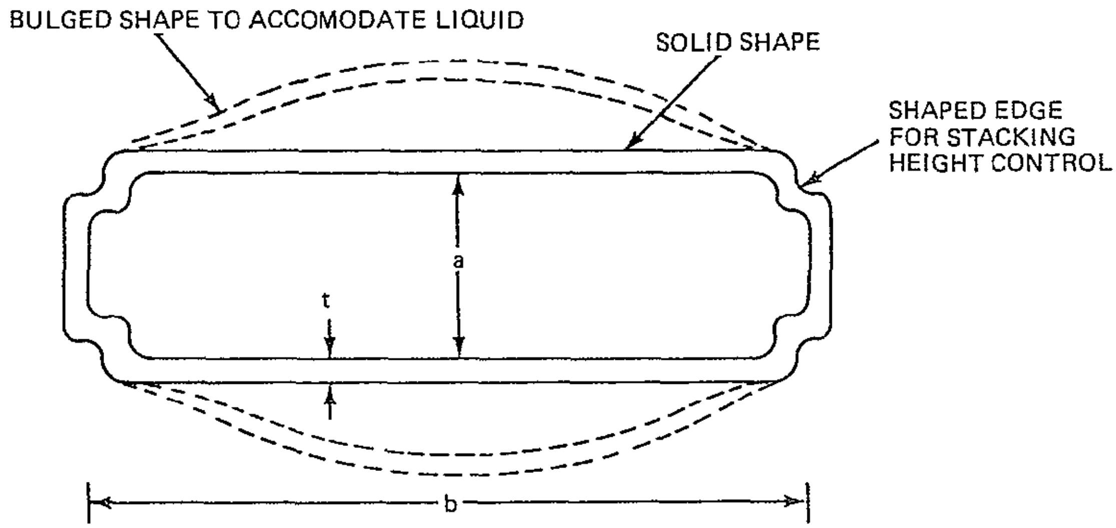
This concept is purely a variant of containment of PCM; no particular cycle configuration was associated with it. In *Thermal Energy Storage Heat Exchanger* by the above authors (Reference 132), a group of alternative heat exchanger concepts for PCM are examined. In addition to variants of conventional tube and shell heat exchangers, a macro-encapsulated PCM concept is described (pp 4-52 to 4-55). Some problems with PCM heat exchange are expansion and contraction with change of temperature and melting/freezing, and low thermal conductivity of the PCM which tends to build upon the heat transfer surface. A candidate solution to both of these is illustrated in Figure 4-32 from said reference.

A solution to the low heat transfer through solid PCM is to provide a large ratio of area to volume of PCM. At reasonable cost this requires very thin walls of low cost material. The upper figure shows the "plank-shaped" blocks of container, thin so that the maximum required penetration distance is small, and wide to give a large area at low cost. If the PCM contained expands or contracts on freezing, the upper and lower walls are free to bulge outward, or bend inward, as shown. The maximum bending stress caused can be low if the walls are thin (stress varies as t^3). The example given suggests a = 7.6 cm, b = 61 cm, t = 0.3 mm.

The notched, shaped edge of the container is designed for easy, stable stacking of containers with a well-defined space between them for fluid flow.

The chapter also discusses briefly:

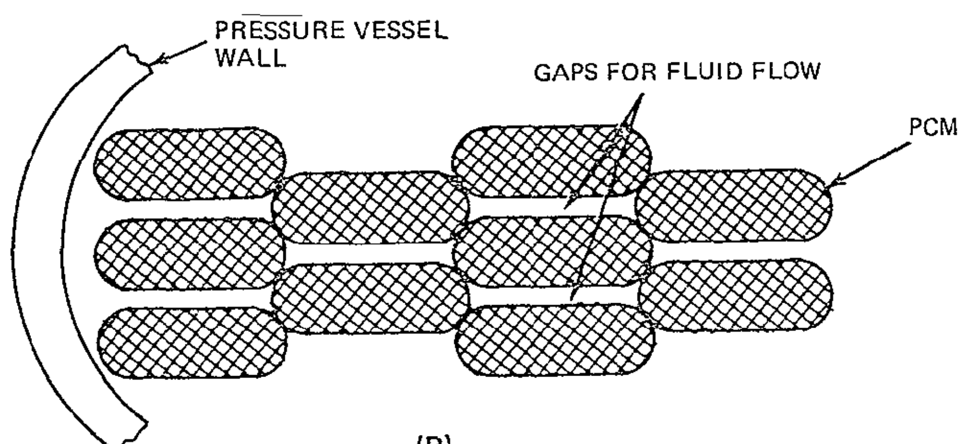
- Fluidized microencapsulation (100µ capsules)
- Intermediate pumped loop (eg liquid metal)
- Scrapers to prevent PCM adhesion
- Heat pipe heat exchangers.



(A)

2349-049D

Macroencapsulated PCM - Cross-Section



(B)

2349-050D

Fig. 4-32 Stacking Arrangement — Macroencapsulated PCM

CONCEPT DEFINITION #49

PROPONENT(S)

General Electric Co.-Schenectady - H. Vakil
F. Bundy

References

119, 146, 149, 154

CHARACTERIZATION

Medium	83	Molten salt (fluorides) M.P. 680°C
Containment	33	Low pressure tank, immiscible fluid
Source of Heat	31	Helium from HTGR
Utilization	1.1	Increased steam flow through main turbine, steam generated through indirect heat transfer with PCM

DESCRIPTION

This concept features a base load nuclear power plant integrated with a thermal storage unit which supplies peak power. The thermal energy is stored in the form of latent heat The PCM used is a NaF-FeF_2 eutectic which has a melting point of 680°C. The eutectic slush is melted during charging by the helium heat exchanger at the right of the figure. This helium then goes to a helium-steam boiler.

On discharge, to avoid poor heat exchange from solidification of the eutectic an intermediate immiscible-fluid direct-contact heat exchanger loop is used. Molten lead is used in the loop. Droplets of molten lead at 370°C enter the top of the storage vessel. They are heated to 680°C by latent heat flow from the eutectic during their descent. The thin crust of solid eutectic easily breaks up when the lead impacts the eutectic slush and pool of molten lead at the bottom. The molten lead then goes to a lead-steam boiler to generate steam at 538°C. In order to keep the salt from solidifying into a solid impermeable layer, helium is bubbled up from the bottom of the salt tank to agitate the salt and keep it broken up into small particles. This process is continued to a point where the slush is close to impenetrable.

For peak power generation the main turbogenerator set is overloaded by the steam generated from the stored thermal energy.

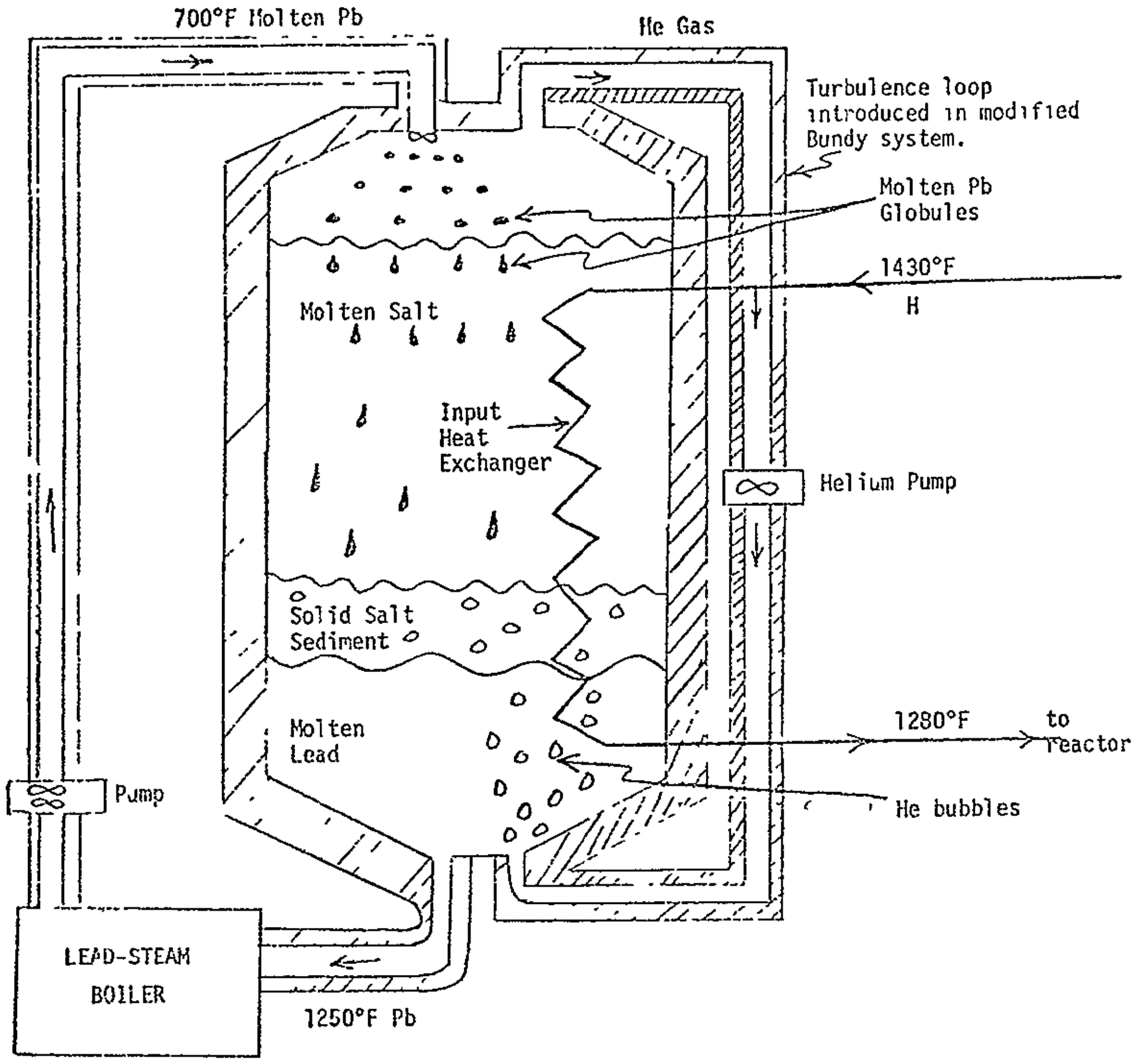


Figure 8 Sub-system to break up solid salt sediment layer in heat bank.

CONCEPT DEFINITION #50

PROPONENT(S)

Rocket Research Co. - E.C. Clark

References

98, 157

CHARACTERIZATION

Medium	33	Sulfuric acid, various concentrations
Containment	2	Low pressure tanks (see discussion)
Source of Heat	-	Unspecified
Utilization	-	Unspecified

DESCRIPTION

The referenced work reports the heat capacity and enthalpy of the sulfuric acid-water system at temperatures to 290°C and the heat of reaction and adiabatic reaction temperature for the dilution reaction of sulfuric acid of various concentrations and initial temperatures. This work is primarily oriented to the laboratory scale investigation and system scale conceptualization of a thermal energy storage system based on the heat of dilution of concentrated sulfuric acid. At the system level, the application envisioned is the use of concentrated solar energy to separate water from 70% sulfuric acid during summer levels of insolation, and to recover the heat by combining the resultant 98% acid and the water during the winter for building heating.

In the present context, interest in this work is confined to information relevant to the use of sulfuric acid of various concentrations as a sensible heat storage medium. For this purpose, data dealing with density, viscosity, heat capacity, vapor pressure, thermal conductivity, and material compatibility are required. The present report tabulates heat capacity values in 5% concentration steps and 5°C temperature steps from 0°C to 290°C. The results above 80°C are extrapolations from published data up to that temperature (Socolik, A.S., *Z physik. Chem.* 158, 305 (1932)) with the only verification of the higher temperature values being the "reasonably good agreement" between predicted and measured adiabatic dilution reaction temperatures. A table of material compatibilities indicates that there are several materials that can contain sulfuric acid to at least 300°C including cast silicon iron, Durichlor 51, Duriron D, Pyrex glass, and Teflon TFE (to 260°C).

2-3-78

CONCEPT DEFINITION #51

PROPONENT(S)

Eidgenössischen Inst. für Reaktorforschung (Swiss) - M. Taube

References

166, 204, 205, 206, 207, 208

CHARACTERIZATION

Medium	26	NaOH eutectic
Containment	21	Low pressure storage tank
Source of Heat	26	Live steam from LWR
Utilization	4.22,3.52	Slush to octane to steam (latent/ latent HX)

DESCRIPTION

In this Swiss paper (in German) the authors describe two concepts for latent/latent heat transfer using NaOH and a second component such as CaO or $NaNO_2$ which forms a eutectic slush with a melting point of 260°C. In the first concept, one heat exchanger is used with live steam at 6.42 MPa (280°C) in the tubes and the slush circulated through the shell, to melt the PCM at 260°C. On discharge, the slush converts water at 120°C to steam at 240°C and 1.0 MPa, leaving the slush temperature at 260°C but raising the fraction crystallized. Despite rapid flow there is a chance of a salt film building on the tanks of the HX.

Bild 1: System mit Röhren-Wärmeaustauscher

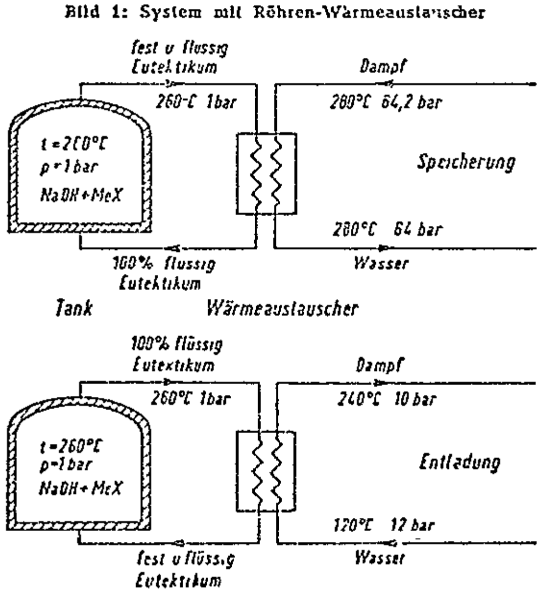
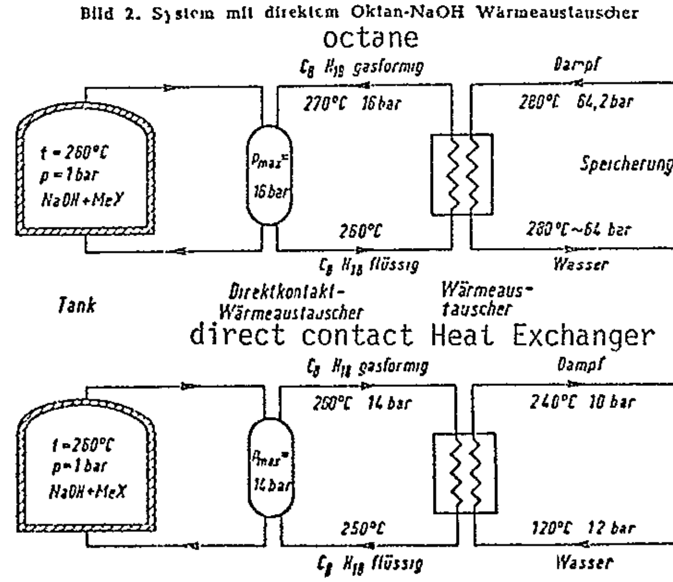


Bild 2. System mit direktem Oktan-NaOH Wärmeaustauscher



ENERGIE, Jahrg 28, Nr 12, December 1976

The second concept cures this with an intermediate working fluid, octane C_8H_{18}. On charge, saturated steam at 6.42 MPa (280°C) heat exchanges to octane at 1.6 MPa (saturation temperature 270°C). Liquid octane is boiled and passed over to a second heat exchanger, in which it is in direct contact with the PCM slush. Slush goes in the top of this direct HX as does the octane gas, which is condensed. Octane liquid is the more buoyant, but it is not made clear how perfect separation is achieved. During discharge the octane pressure is reduced to 1.4 MPa, putting its boiling point below the slush temperature. Direct heat exchange, with liquid octane entering the bottom of the direct contact HX, gasifies the octane which in turn creates steam at 1.0 MPa and 240°C in the indirect HX.

The idea should avoid the conventional film problems of PCM materials, if the separation of liquid octane and slush can be effective.

1 Report No NASA CR-159411 - Vol. 2	2 Government Accession No	3 Recipient's Catalog No
4 Title and Subtitle CONCEPTUAL DESIGN OF THERMAL ENERGY STORAGE SYSTEMS FOR NEAR TERM ELECTRIC UTILITY APPLICATIONS Vol. 2: Appendices		5 Report Date OCTOBER 1978 6 Performing Organization Code
7 Author(s) W. HAUSZ, B.J. BERKOWITZ, R C. HARE		8 Performing Organization Report No GE78TMP-60
9 Performing Organization Name and Address GENERAL ELECTRIC COMPANY—TEMPO P.O. DRAWER QQ SANTA BARBARA, CA 93102		10 Work Unit No 11 Contract or Grant No DEN3-12
12 Sponsoring Agency Name and Address U S DEPARTMENT OF ENERGY DIVISION OF ENERGY STORAGE SYSTEMS WASHINGTON, DC 20545		13 Type of Report and Period Covered CONTRACTOR REPORT 14 Sponsoring Agency ~~Code~~ Report DOE/NASA/0012-78/1

15 Supplementary Notes

TOPICAL REPORT PREPARED UNDER INTERAGENCY AGREEMENT EC-77-A31-1034-2
PROJECT MANAGER, EDWARD R. FURMAN, POWER GENERATION AND STORAGE DIVISION
NASA-LEWIS RESEARCH CENTER, CLEVELAND, OH 44135

16 Abstract

Over forty thermal energy storage (TES) concepts gathered from the literature and personal contacts were studied for their suitability for the electric utility application of storing energy off-peak for discharge during peak hours. Twelve selections were derived from the concepts for screening, they used as storage media high temperature water (HTW), hot oil, molten salts, and packed beds of solids such as rock. HTW required pressure containment by prestressed cast-iron or concrete vessels, or lined underground cavities. Both steam generation from storage and feedwater heating from storage were studied Four choices were made for further study during the project

Economic comparison by electric utility standard cost practices, and near-term availability (low technical risk) were principal criteria but suitability for utility use, conservation potential, and environmental hazards were considered

17 Key Words (Suggested by Author(s)) Thermal Energy Storage, Heat Storage, Off-Peak Energy Storage, Underground Storage Electric utilities, load management, electric power demand, electric power generation, steam turbines, nuclear power plants, fossil-fired power plants. Cost analysis, pressure vessels, containment systems, heat transfer fluids, heat exchangers.	18 Distribution Statement UNCLASSIFIED—UNLIMITED STAR CATEGORY 44 DOE CATEGORY UC-94a

19 Security Classif (of this report)	20 Security Classif (of this page)	21 No of Pages	22 Price*
UNCLASSIFIED	UNCLASSIFIED	142	A07

*For sale by the National Technical Information Service Springfield Virginia 22161

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